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CLIMATOLOGY AND LOW-LEVEL AIR POLLUTION POTENTIAL FROM SHIPS IN THE HAMPTON ROADS

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U. S. NAVY WEATHER-RESEARCH FACILITY
BUILDING R-48, U. S. NAVAL AIR STATION
NORFOLK, VIRGINIA 23511

JUNE 1964

CORRIGENDA

Location				Correction
Page	Column	Paragraph	Line	
1	-	6	3	2×10^9
1	-	6	3	clima-
1	2	2	15	plume
5	2	1	17	$\bar{u}$
9	1	4	11	26.6×10^9
10	1	2	3	2×10^9
15	2	3	9	gravitational
16	1	2	4	$e^{\frac{-\lambda x}{\bar{u}}}$
17	1	1	-	Equation 2.2: $e^{\frac{-\lambda x}{\bar{u}}}$
52	-	-	-	Figure 3.29 is upside down

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FOREWORD

This report was prepared under Task 39 which was assigned to the Navy Weather Research Facility for the purpose of determining the meteorological effect upon a polluting material released into the atmosphere within ports and harbors of interest to the Navy.

The publication investigates the pollution potential from ships in Hampton Roads. A similar publication for San Diego Harbor has previously been published; however, the present report embodies some more recent developments in the calculations of atmospheric diffusion.

A general estimate of the microclimate of the Hampton Roads area is presented, since detailed data are not available on the microclimatic scale. A complete microclimatic investigation on the time and space variation of wind, temperature gradient, and precipitation within this region would be extremely complex and too ambitious a task for the purpose of this report. Consequently, though such a study may be desirable, it has not been attempted. Available meteorological records for the Hampton Roads region have been utilized, and from these data, parameters have been chosen which are considered most useful in evaluating the travel and dispersion of airborne material. The effects of these parameters are discussed, and general summaries of their diurnal, seasonal, and monthly changes have been prepared.

The estimates of the dispersion of pollutant materials, released to the lower atmosphere (to approximately 2,000 feet), are presented within the limits of our current knowledge on this scale. However, the general nature of the estimates of extent and ground-level concentration of the contaminant leave room for improvement, possibly by more detailed meteorological information or research into the dispersion of materials on this scale of interest.

The order of presentation of the work differs from the usual and should be explained. It is customary in meteorological studies to begin with a detailed description of the site and its climatology, and then to show the significance of these features in terms of the problem. This presupposes considerable familiarity with the subject and is the actual order of the original development of the work. However, the processes described are not especially familiar, and the significance of the climatological variations is much clearer, if reviewed after an understanding of the problem is assured.

Chapter 1 is intended to give the reader an introduction to and hopefully an understanding of the basic concepts in diffusion meteorology. Chapter 2 deals with calculations of the various diffusion patterns, using a hypothetical release of 2×10^{6} units. Chapter 3 presents the climatology of the Hampton Roads area, stressing the meteorological parameters most important from an atmospheric pollution standpoint. Chapter 4, the concluding section, specifically discusses the pollution potential of Hampton Roads from the theory discussed in chapter 1 and the calculations and the data presented in chapters 2 and 3.

The report was assembled from current literature and existing data and was written by Mr. René V. Cormier, Assistant Task Leader, under the supervision of the Task Leader, Mr. John M. Mercer, who also edited this publication.

This report has been reviewed and approved on [illegible] July 1964 by the undersigned.

James L. Kerr

JAMES L. KERR
Commander, U. S. Navy
Officer in Charge
U.S. Navy Weather Research Facility

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TABLE OF CONTENTS

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TABLE OF CONTENTS (CONTINUED)

Best Available Copy

LIST OF FIGURES AND TABLES

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LIST OF FIGURES AND TABLES (CONTINUED)

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Tables (2):

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1. PRINCIPLES OF DIFFUSION

1.1 Transport and Dilution (18)

The diffusive capacity of the atmosphere is superimposed on the general air motions and will affect any foreign matter injected into the air, whether it is a smoke, gas, mist, or dust. In order to understand the role of the atmosphere in moving pollutants it is necessary to recognize that the two processes, transport and dilution, operate simultaneously. The general direction that a pollutant will take after being introduced into the atmosphere can be estimated with some precision from the general flow patterns indicated on a synoptic chart. The direction, at any point, will change with time as the large scale weather systems move and change their intensity. If, however, we scrutinize the weather map in detail, through a microscope as it were, smaller irregularities in the flow become evident; not only has the scale been increased but more observations have been used to deliniate some of the irregularities. The sharp discontinuities in the wind field and the small so called "meso" *highs* and *lows* , too small to be seen on the map of the entire United States, now become visible. The systems observed on this scale have life spans on the order of a few hours to less than a day. If we now increase the magnification even further, say looking at a cigarette, we would see that in the space of just a foot or less, the smoke from the cigarette would twist and turn in response to atmospheric motions as small as an inch, or if we had unusual visual acuity, even less. Perturbations of such small size probably disappear in a matter of a few seconds. This above progression serves to illustrate the increasing complexity of the atmosphere as we regard it in increasingly greater detail.

The mixing of material with the atmosphere is caused almost entirely by what is called eddy motion , which may be mechanical or thermal in origin or due to both effects in combination. Anemometer records show that in general, and especially in the lower layers of the atmosphere, the wind is highly turbulent with the velocity oscilleting with periods varying from a fraction of a second to several minutes and with an amplitude which is often a substantial fraction of the average speed. Similarly, direction indicators show irregular oscillations so that the wind vector is constantly changing not only from one instant to another but also from one point to another. The eddies which give rise to these velocity fluctuations cover an almost infinite range of size and the diffusive action of a particular eddy depends mainly on its size. A small parcel of a contaminant may be merely transported as a whole by a large eddy whereas a small eddy would be an effective diffusing agent. In the case of continuous discharge of effluent, some eddies promote diffusion of the plume, and therefore mixing with the surrounding atmosphere, while other eddies move the plume in a serpentine fashion horizontally and vertically; in general the puff of pollutant will move in the direction dictated by those motions larger than the puff, while the diffusion of the puff will be caused by those motions smaller than the puff.

1.2 Studying Smoke Plumes (18)

The relationship between atmospheric motions and diffusion may be further investigated by studying the patterns assumed by smoke plumes (which may be thought of as a continuous string of puffs) from a chimney and relating these plumes to concurrent wind fluctuations as observed by a recording wind vane and anemometer. Figure 1.1a shows an instantaneous snapshot from *above* a chimney emitting smoke. If we were to measure the percentage concentration of the smoke across the plume at the slice A-A we might well have a pattern similar to that in figure 1.1b. We would find that the concentration values vary erratically across the plume and drop to zero at the edge of the plume. Now instead of an instantaneous picture, if we were to take a 5-minute time exposure of the smoke plume (fig. 1.2a), we would note some substantial changes. The irregular edge of the instantaneous plume would be replaced by smoother, regular edges. The crosswind concentration curve through A-A would also be more regular and would be distinctly higher at the center than at either edge. The concentration along the axis of the plume would decrease inversely as the cross-sectional area of the plume increased. Had we placed a wind wave near the mouth of the chimney and measured the wind direction we might find that the recorder trace looked like that in figure 1.2c. The direction is rarely, if ever, steady even over a period this short. A histogram constructed from instantaneous direction values taken at one second intervals is shown in figure 1.2d. The similarity between figure 1.2b and 1.2d is not acci-

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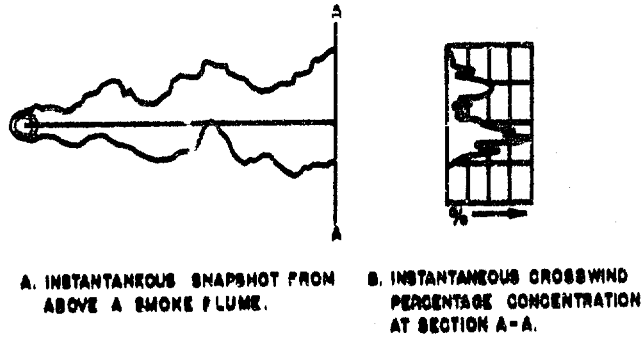

Figure 1.1. Configuration of a Smoke Plume. [from Slade, 18]

dental. If the wind at a given instant is from, say, 280° then the smoke from the chimney in that instant will move, generally, with the wind and intersect A-A at 280°. At each succeeding second the emitted smoke will move with the wind direction at that second. Thus, curves 1.2b and 1.2d will be similar. This relationship is not quite as simple as stated here. A particle of smoke need not maintain its initial direction indefinitely. Much recent study has been devoted to this subject.

For our present purposes, however, it is only necessary to recognize that the result of *averaging* the data over a few minutes has been to smooth out the irregularities in both smoke concentration and wind direction frequency distributions.

Vertical as well as horizontal wind fluctu-

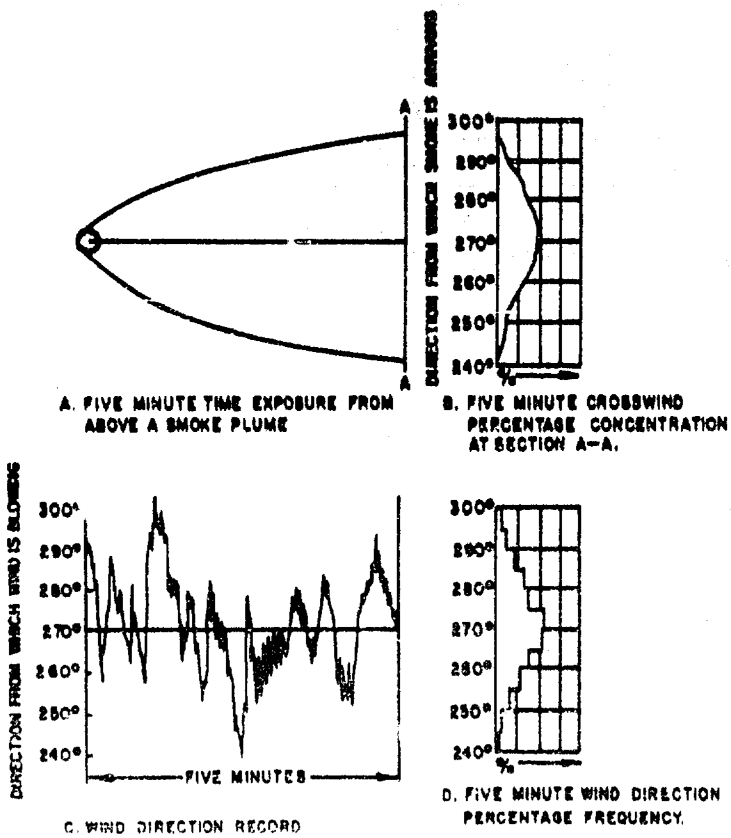

Figure 1.2. The Average Shape of the Plume. [from Slade, 18]

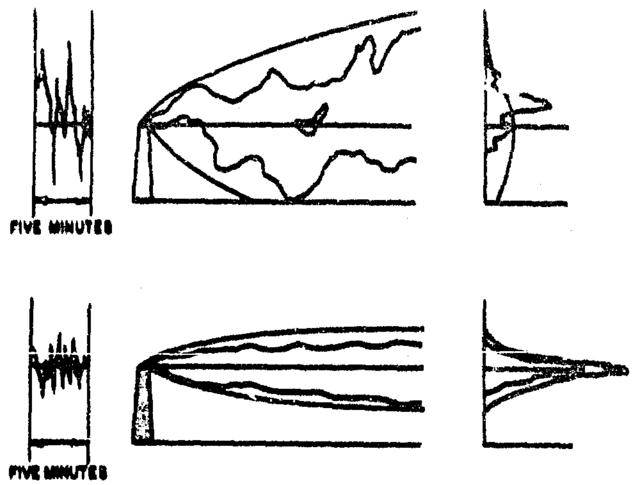

Figure 1.3. Examples of Vertical Wind Fluctuations. (from Slade, 18)

ations are of importance in assessing diffusion. Figure 1.3 shows how the vertical wind fluctuations might appear. Their effect on plume shape and concentration is also shown.

The fact that the apparently chaotic atmospheric motions may be shown to fall into smooth and regular patterns by the application of suitable averaging techniques has enabled meteorologist to forecast, with some accuracy, the extent to which an atmospheric contaminant will be diffused. The magnitude of the fluctuations may be related to the vertical atmospheric temperature structure, which in turn is related to the intensity of solar radiation (or the lack of it) and the speed of the wind. When the insolation is intense and the wind is light (convective instability), as might be the case on a clear summer day, atmospheric motions, both vertical and horizontal, will be initiated or enhanced. When solar insolation is weak or absent and the wind speed low, as on a clear night, temperature decreases slowly or even increases with height (inversion condition) tending to inhibit turbulent motions. Neutral conditions commonly occur when the sky is overcast or in the presence of strong winds which mix the air very thoroughly. High wind speeds tend to reduce the fluctuations during strong insolation conditions and increase fluctuations when the insolation is small. Figure 1.4 serves as a guide for depicting, schematically, model effects of vertical stability on despersion. Near the ground, the state of the atmosphere can differ markedly from that depicted by radiosonde observations; i. e., lapse rates are usually steeper during insolation conditions and more stable during inversions.

1.3 Theoretical Studies

A number of theoretical studies have produced fairly straight forward methods for estimating the history of contaminants introduced into the atmosphere. However, it is necessary to keep in mind that these theoretical treatments are so highly idealized that their limitations must be understood if serious errors are not to be made.

1.3.1 Sutton [21, 22, and 23]

The well-known theory developed by Sutton, along semiemperical lines, provides a satisfactory means of estimating concentrations in a cloud or plume of effluent for distances of travel of about 1 kilometer and for atmospheric conditions corresponding to neutral equilibrium. Sutton's theory is formally complete in that it investigates the effects of wind speed, turbulence, and atmospheric stability; however, it is too restrictive for real-life application, where atmospheric conditions are more often other than neutral and where interest lies beyond distances of 1 kilometer. Extended applications of the theory (treating Sutton's diffusion parameters more as adjustable constants than as fundamental quantities) to varying degrees of atmospheric stability, to greater distances, and to all kinds of terrain have been attempted but have been less successful.

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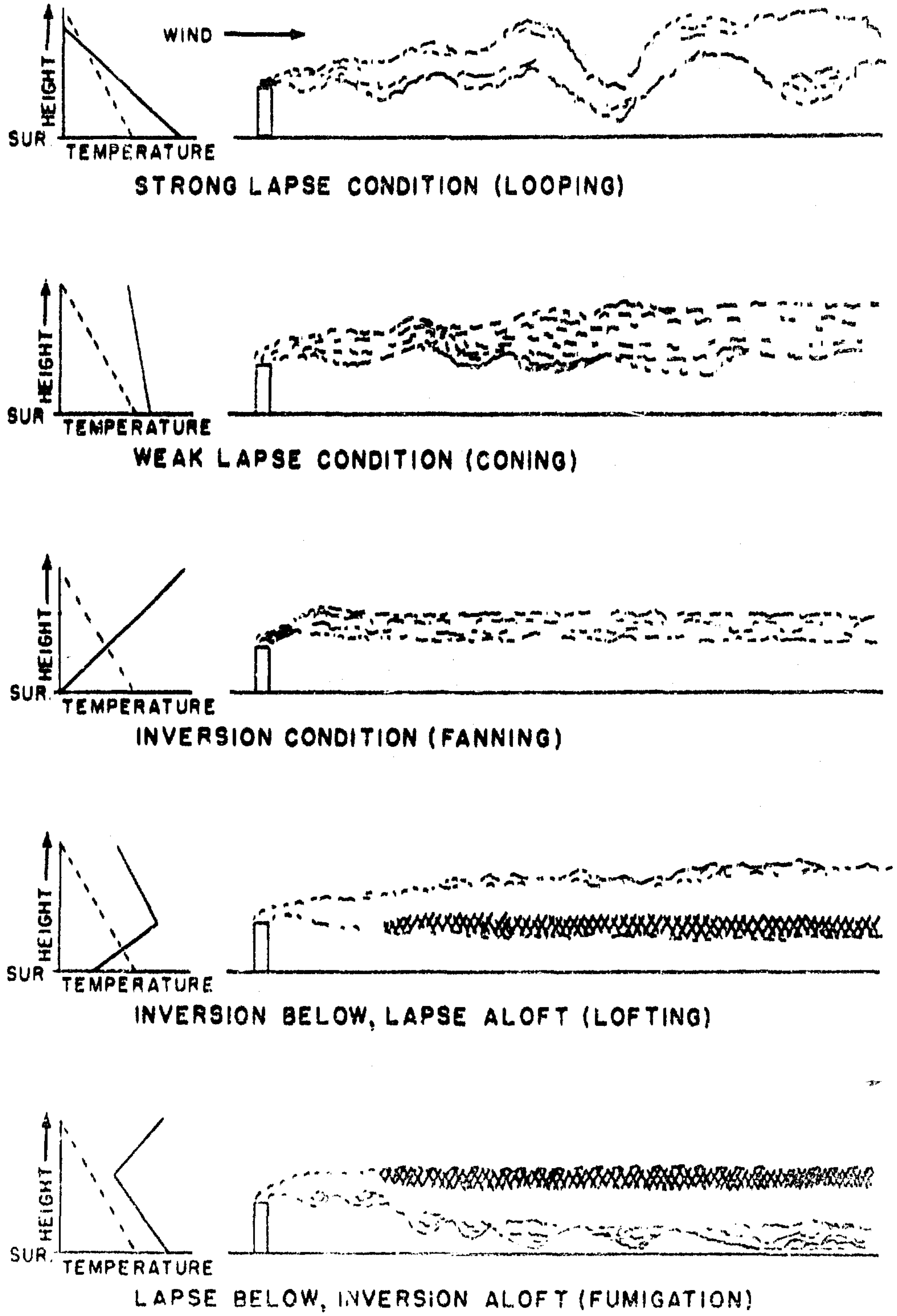

Figure 1.4. Modal Effects of Vertical Stability on Diffusion.

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1.3.2 Pasquill and Meade [12, 13, and 14]

In light of the above considerations it is clearly desirable to take a more direct account of conditions actually prevailing in the atmosphere over the distance and height for which concentrations are to be estimated. In England, Pasquill and Meade, along these lines, recently proposed a simple system of estimating atmospheric dispersion from a continuous point source that seems likely to find widespread acceptance among workers in the field of diffusion. It embodies the main principle of Sutton's work but applies the appropriate atmospheric conditions directly.

These investigations have shown that a fairly rational allowance can be made for the effects of much of the wide variation in atmospheric turbulence which occur in reality over a particular distance from a pollutant source. Although many aspects of the problem require further attention, these recent developments, supported also by experimental studies in this country, form a basis for a tentative system of estimating diffusion within a wide range of meteorological conditions and over distances of up to 100 kilometers.

(a) Basic Assumption

A cloud of smoke or other airborne substance, continuously generated at ground level, drifts downwind as a long plume; its width and height increasing with distance travelled in accordance with the degree of turbulence present. If measuring instruments are placed at varying distances and at varying heights downwind and across wind, it is found that for any plane perpendicular to the direction of the wind, the concentration decays horizontally and vertically with a distribution that closely resembles a Gaussian error curve (a "normal" distribution). This means that the concen tion drops off symmetrically in any two directions from the line of maximum concentration according to a normal error law, as illustrated in figure 1.5. This assumption forms the basis for succeeding developments.

(b) The Gifford Modification [10]

The work of Pasquill and Meade expressed in a slightly modified form suggested by Gifford (1961) yields the so-called generalized Gaussian plume formula of the basic dispersion equation, (also known as the Gaussian interpolation formula)

$$\chi_{(x,y,0)} = \left(\frac{Q}{\pi \sigma_y \sigma_z \bar{u}}\right) e^{-\left[\frac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2}\right)\right]} \qquad (1.1)$$

where:

χ = (depending on the units of Q) ground level air;

(1) concentration (units per cubic meter) or

(2) dosage (units-seconds per cubic meter)

Q = source strength, either;

(1) continuous source (units per second) or

(2) instantaneous source (units)

π = 3.14

σ_y = lateral dispersion coefficient (meters)

σ_z = vertical dispersion coefficient (meters)

$\bar{u}$ = mean wind speed (meters per second)

e = the exponential

y = crosswind (lateral) distance from plume axis (meters)

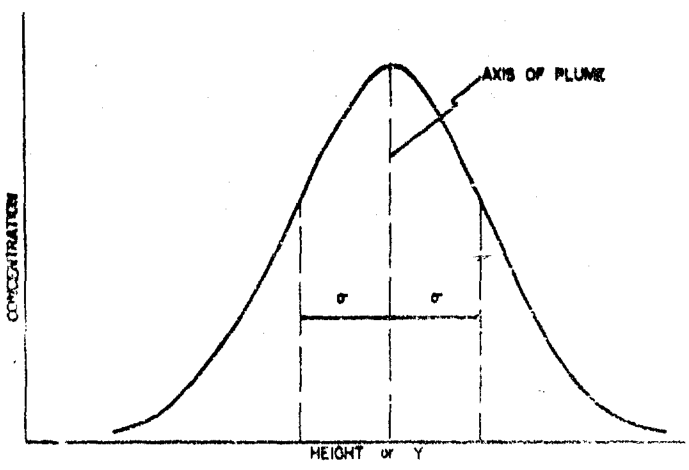

Figure 1.5. Normal Distribution of Air Pollution.

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h = height of the source above the ground (meters)

The modification consists of expressing the dispersion coefficients in the y and z directions as standard deviations of the plume distribution, σ_y and σ_z, rather than the points at which the concentration falls to 10 percent of its axial value (a figure representing the visual extent of most smoke plumes). The right-hand side of equation 1.1 contains a multiplicative factor of 2, which is a conventional device to account for the assumed reflection of the plume by the ground plane.

In order to solve the equation, Pasquill [13] proposed families of curves of dispersion coefficients versus distance from the source; these are based both on recent concentration measurements and on theoretical expections. In terms of σ_y and σ_z the values are given in figure 1.6 and figure 1.7, from Gifford [10]. Table 1.1 [10 and 11] should be used in conjunction with these figures; it shows how the stability categories *A* through *F* are related to wind speed, insolation, and the state of sky. *Strong* insolation, for example, refers to sunny conditions around midday in midsummer, while *Slight* insolation refers to the corresponding conditions in midwinter. Using equation 1.1, figures 1.6 and 1.7, and table 1.1, graphs of downwind concentrations may be prepared.

(c) Compared with Sutton

Generally speaking, concentration patterns computed with equation 1.1 will closely resemble those computed by Sutton's traditional method. The chief difference lies in the behavior for

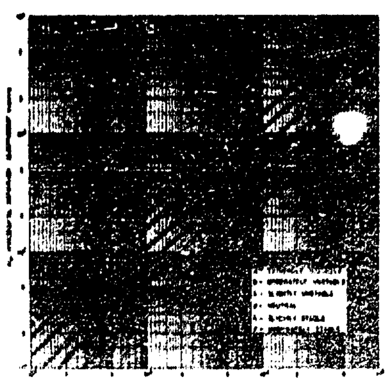

Figure 1.6. Horizontal Dispersion Parameter σ_y (meters), as a Function of Downwind Distance, x (meters), for Various Weather Types.

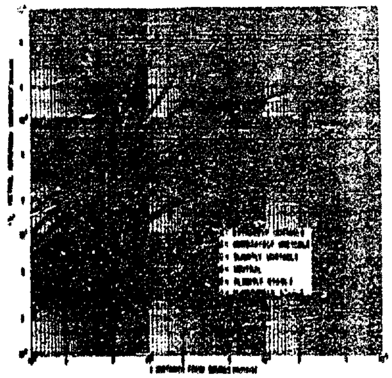

Figure 1.7. Vertical Dispersion Parameter σ_z (meters), as a Function of Downwind Distance, x (meters) for Various Weather Types.

distances beyond about 10 kilometers. Downwind ground concentrations computed for a type *F* condition, at greater distances, are higher than concentrations computed using stable diffusion coefficient values in Sutton's formula. This point has significance in connection with environmental studies of hazards associated with newer power systems for which concentrations have commonly been computed for downwind distances far in excess of 1 kilometer, to which Sutton's formula was originally intended to apply.

(d) Uncertainties [12]

The method proposed above involves a number of uncertainties, for example in the estimates of vertical spreading, and so it should be regarded as giving only approximate but realistic estimates of the magnitudes of the concentrations at various distances from the source. In some of the more difficult cases involving stable and unstable conditions, errors of several fold in vertical spread could be made. This should be kept in mind when applying this technique to the assessment of hazards. On the other hand, there will be relatively straight forward cases where estimates of vertical spread may be expected to be correct within a factor of 2, for example:

(1) All stabilities, except extremes, for distances of travel of a few hundred meters in open country.

(2) Neutral conditions for distances of a few kilometers.

(3) Unstable conditions in the first 1,000 meters above ground, with a marked in-

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Table I.1. Meteorological Categories.

SURFACE WIND SPEED m./sec. (knots)	*DAYTIME INSOLATION* Strong	Moderate	Slight	*NIGHTTIME* Thin overcast or $\geq$ 4/8 cloudiness[1] (5 tenths)	$<$ 3/8 cloudiness (4 tenths)
<2 (<4)	A	A-B	B	E	F
2 (4)	A-B	B	C	E	F
4 (8)	B	B-C	C	D	E
6 (12)	C	C-D	D	D	D
>6 (>12)	C	D	D	D	D

A: Extremely unstable conditions

B: Moderately unstable conditions

C: Slightly unstable conditions

D: Neutral conditions[2]

E: Slightly stable conditions

F: Moderately stable conditions

[1] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds. [Manual of Surface Observations (WBAN), Circular N (7th ed.), paragraph 1210, U. S. Government Printing Office, Washington, July 1960.]

[2] Applicable to heavy overcast, day or night, if ceiling is less than 7,000 feet.

Note: For A-B take the average of curves A and B, etc.

DAYTIME

Solar Altitude (α)	*Insolation*
$\alpha > 60°$	*Strong*
$35° < \alpha \leq 60°$	*Moderate*
$15° < \alpha \leq 35°$	*Slight*
$\alpha \leq 15°$	*Weak (use nighttime)*

Daytime Cloud Cover Effect on Insolation

1. *If clouds 5/10 or less, no change.*
2. *If clouds more than 5/10:*
   - a.) *Ceiling below 7,000, change: A to C, B to D, C to D.*
   - b.) *Ceiling 7,000 or above but below 15,000, change: A to B, B to C, C to D.*
   - c.) *Ceiling 16,000 or above and broken, no change.*
   - d.) *Ceiling 16,000 or above and overcast (heavy), change: A to B, B to C, C to D.*

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version immediately above, for distances of travel of 10 kilometers or more.

For the most part, uncertainties in the lateral spread of the plume are likely to be less important than in the case of vertical spread, except when the wind field is indefinite. In such circumstances, a more important source of error is that involved in estimating the position of the plume, and it is best to allow for a wide range of possible directions of the plume.

(e) Present Value

The curves presented in figures 1.6 and 1.7 will, in all likelihood, have to be modified as air concentration measurements, particularly at the greater distance, become available. A recent series of diffusion observations [12] has, however, verified the above method out to distances of 5 kilometers from the source. Nevertheless, use of these dispersion estimates in connection with ship pollution potential studies, as well as other air pollution problems, particularly in the form of the plume standard deviation presented here, seems to be very desirable. It is a straightforward approach that directly reflects the best current observational knowledge of air concentration downwind from an isolated source.

The generalized Gaussian dispersion formula is, briefly, both adjustable and compatable, and thus provides an appropriate framework into which we can fit existing atmospheric dispersion knowledge, both theoretical and observational, as well as anticipated future improvements.

1.3.3 Transitional States

Another concept which has a direct bearing on the concentration of a pollutant from ships, or any source, and about which little is known is that of diffusion in "transitional states". This simply means that the atmospheric turbulence often displays a marked variation in time or space, or in both. The variation of turbulence in the horizontal plane along a line perpendicular to a shoreline can be significant. These horizontal variations can be due to temperature differences in the underlying surface, or they can be due to roughness differences in the underlying terrain. Both thermal and mechanical turbulence can be initiated or suppressed depending on whether the air flows over water or over land first.

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2. CALCULATIONS

The calculation of the effects of a release of decaying products is hindered by lack of knowledge of the nature of the source, in particular the source strength, the distribution of particle sizes, and the height of rise of the cloud. Recognizing these difficulties the methods described may be used to calculate the *upper limit* of the air concentration near ground level.

2.1 Initial Behavior of Cloud

The initial conditions of release would have an important bearing on the fate of a pollutant cloud, which might consist of a gas or a vapor or very small solid particles. In addition to the amount of pollutant, the cloud temperature and the time period over which the release occurs would both be significant. A rapid release of warm effluent will form a rough sphere that will tend to rise until it reaches the density of the surrounding air. A slower release of the same amount of warm effluent will give a much lower cloud height. Variations in the existing atmospheric temperature, lapse rate, and turbulence will also have an important influence upon this process.

Both the rapid and the slow (cold) releases are considered in this report. The upward motion of the warm cloud must be taken into account, and the cloud is represented initially as a sphere having a uniform temperature. This "bubble", of lower density than its surroundings, will rise and move downwind simultaneously. The temperature differential is continuously reduced by entrainment, by adiabatic expansion as it rises to regions of lower pressure, and by thermal radiation until it attains the density of the surrounding air.

The selection of a mathematical model for this process and the choice of appropriate values for the parameters presents a difficult problem. In lieu of anything superior, a height rise formula developed by Sutton (20, 21) has been chosen to represent daytime (lapse) conditions in this study. It is relatively conservative in terms of low-level behavior, in the sense that it predicts a modest rise. For a release sufficient to rupture a heavy metal container (28.3×10^{3} cal.), the equation predicts a cloud height of 860 meters.

A similar treatment is used to estimate the height to which the cloud representing the same release would rise at night. The Sutton formula gives a negative result with a temperature inversion and the Holland modification (23) has been substituted. As would be anticipated, this Holland modification gives a smaller rise, 400 meters. Both calculations apply only to clouds consisting essentially of dry air at 3000°F. It is doubtful whether any refinements in the above treatment would have yielded any greater precision.

It is proper to question, however, the error in these estimates, since the ground level concentrations calculated in later work are strongly dependent upon them. This is difficult with the available data, but it seems doubtful that a cloud would reach a height more than twice that calculated.

It is easier to define the other (lower) limit, since a release of the pollutant material might occur slowly at essentially the temperature of the surrounding atmosphere. This implies no ascent of the cloud, and is treated as such. In this case the contaminant is postulated to be released without a large source of heat and may be approximated as a cloud at ground level. This type of release would be the more hazardous, and a solution using this assumption would be pessimistic since a cloud in all probability would have some rise.

2.2 Diffusion of the Cloud

The generalized Gaussian dispersion equation (previously presented) applies when estimating ground concentrations, with the x-axis oriented downwind and the y-axis crosswind. When the source is at the surface (cold release), h is equal to zero and the term containing h drops out of the equation. For determining the line of maximum downwind ground accumulation (x-axis), y would also be equal to zero. Therefore, when both h and y are equal to zero (surface source, x-axis accumulation), the entire exponential term would be equal to one and the equation reduces to:

$$\chi_{(x,0,0)} = \frac{Q}{\pi \sigma_y \sigma_z \bar{u}} \qquad (2.1)$$

In the case of the hot release, the term containing h remains in the equation.

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It is difficult to specify both the rate and the time interval over which the release would occur, but if the total release, is substituted for the rate of release, the result can be given in terms of dosages (that is units-sec./m.^{3}) instead of concentration (units/m.^{3}). Dosage refers to the total integrated amount of polluting agent for a given pollution incident, while concentration refers only to an instantaneous amount of pollutant.

The results of the diffusion computations are summarized in figures 2.1 through 2.16. A somewhat arbitrary release of 2 x 10^6 units is assumed for the calculation. This figure is a pessimistic one derived for a power source much larger than is probably in existence or contemplated for naval ships; thus, the diffusion patterns which will result from the use of this figure are on the cautious side. Dosages for a smaller release may be derived as a direct percentage of those given in the figures since only the Q will differ in the equation.

2.2.1 Centerline Dosages, Cold Release

Figures 2.1 through 2.5 refer to the cold release in which the cloud centerline begins and remains at the ground. This approximation is obtained by setting $y = h = e$ in equation 1.1. The centerline dosages are presented for both day and night; three degrees of insolation are considered for diffusion during the day and two con-

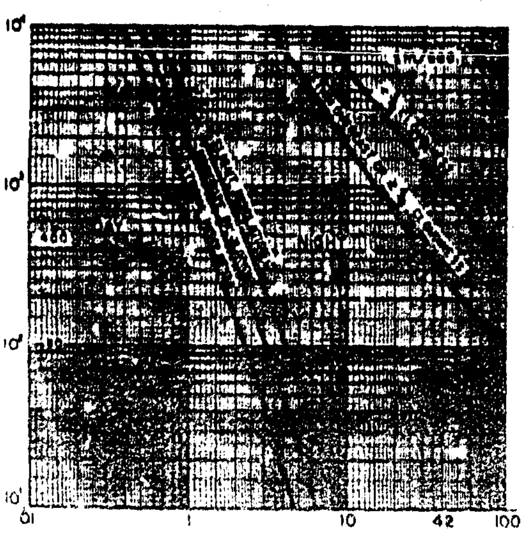

Figure 2.1. Downwind Centerline Dosages, Ground Level Cloud, Wind Speed, < 2m./sec.(1m./sec. for example).

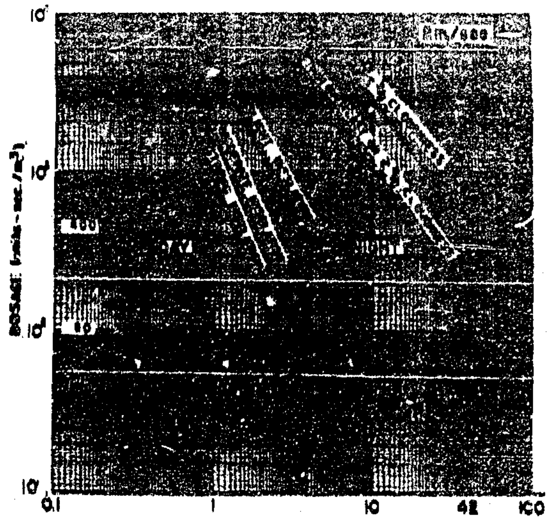

Figure 2.2. Downwind Centerline Dosages, Ground Level Cloud, Wind Speed, 2m./sec..

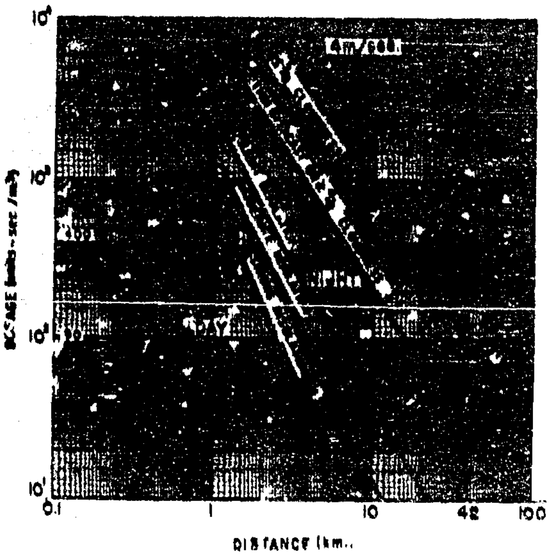

Figure 2.3. Downwind Centerline Dosages, Ground Level Cloud, Wind Speed, 4m./sec..

ditions of cloudiness for night patterns. The day and night isopleths are presented for wind speeds ranging from 2 knots (1 m./sec.) to 20 knots (10 m./sec.). The calculations extend to 100 kilometers (62 miles), which is a limit suggested by Pasquill in the application of his techniques. In the worst case of diffusion, that of a nighttime inversion condition and a wind speed of 1 meter per second, a pollutant would travel approxi-

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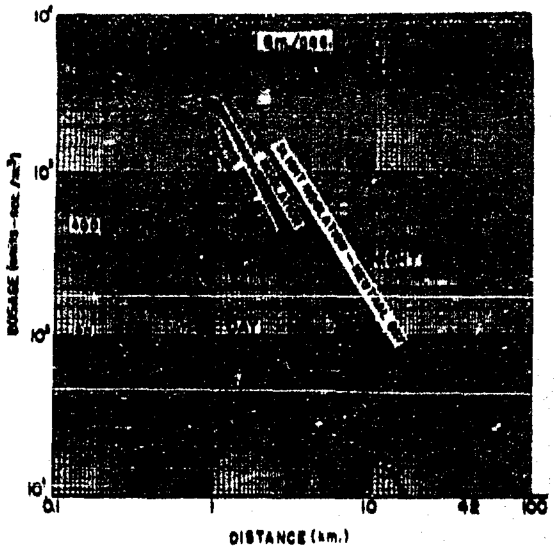

Figure 2.4. Downwind Centerline Dosages, Ground Level Cloud, Wind Speed, 6m./sec.

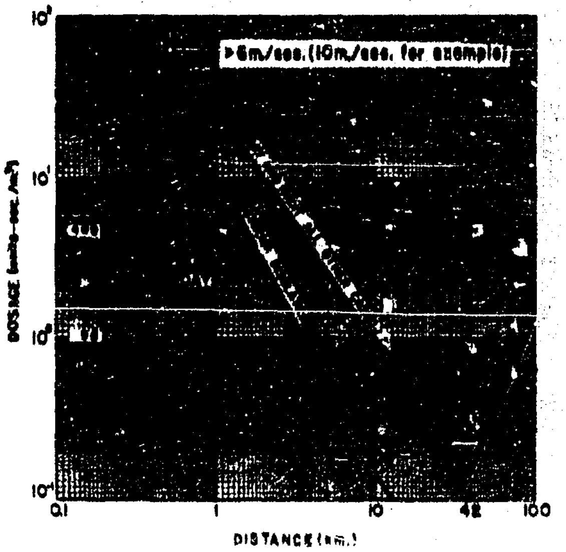

Figure 2.5. Downwind Centerline Dosages, Ground Level Cloud, Wind Speed, >6m./sec.(10m./sec. for example).

mately 42 kilometers in a 12-hour period; this condition would, in most cases, be followed by some sort of lapse condition which would disperse a pollutant in a distance of about 10 kilometers. Thus, the 100 kilometer limit, although at first glance restrictive, is more realistic than, say, extending the calculations to 1,000 kilometers.

The very great difference between night and day, in the lower speed categories, is immediately evident. A dosage of 10 units (bottom of the ordinate scale) for a day with strong insolation and a wind speed of 1 meter per second extends to a distance on the order of 5 kilometers; whereas on a clear calm night the same dosage would theoretically extend (if conditions remained unchanged) to hundreds, if not thousands of kilometers. This great difference between night and day, is due mainly to differences in the vertical diffusion coefficients (see fig. 1.7). As wind speed increases, however, the difference between night and day decreases, so that for wind speeds greater than 12 knots (6 m./sec.) both day and night are similar, except for days of very strong insolation. The higher wind speeds tend to create deep layers of neutral stability. Along these same lines, the effect of cloudiness on dispersion at night and insolation during windier days, tends to disappear as wind speed increases. However, in the lower wind speeds, significant differences in the dispersion distance of a pollutant exist for varying degrees of insolation by day and cloudiness at night.

2.2.2 Centerline Dosages, Hot Release

Figures 2.6 through 2.9 represent the same dosage information derived from the assumption of a rapid, hot release sufficient to rupture the container, but including the same amount of pollutant. In these cases, the contaminant

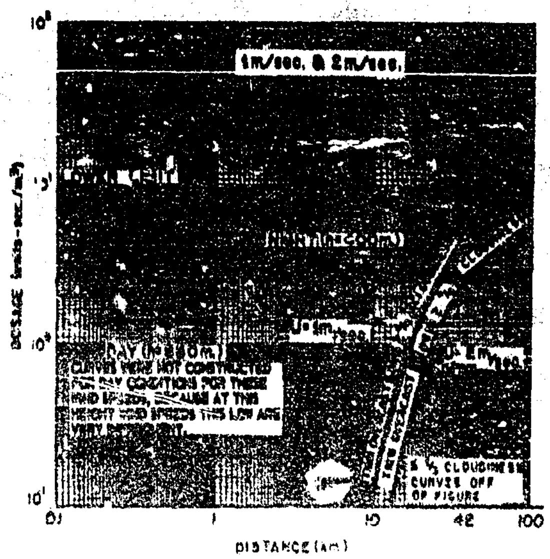

Figure 2.6. Downwind Centerline Dosages, Hot Cloud Aloft, Wind Speeds, <2m./sec.(1m./sec.) and 2m./sec..

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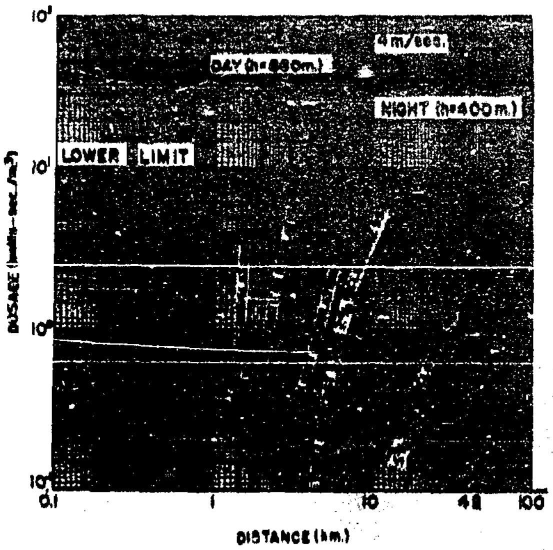

Figure 2.7. Downwind Centerline Dosages, Hot Cloud Aloft, Wind Speed, 4m./sec..

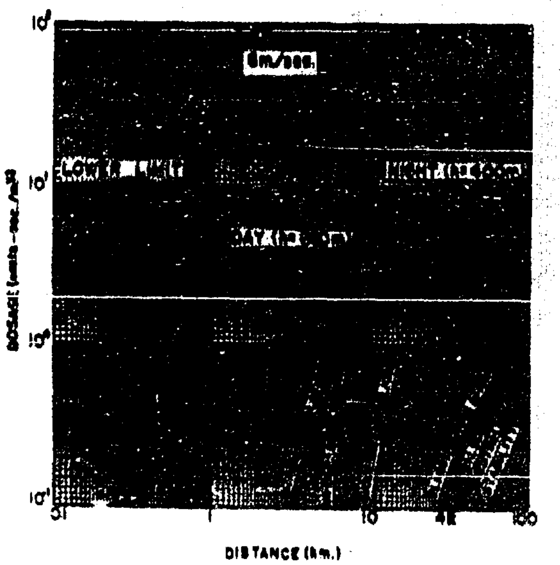

Figure 2.8. Downwind Centerline Dosages, Hot Cloud Aloft, Wind Speed, 6m./sec..

is not continuously present at the ground because of the fact that the cloud first rises and then diffuses back toward the surface. This results in what might be described as a skip-distance between the source and the bulk of the ground contamination. In practice there would be some pollutant present in this region, between the source and the area predicted by the equation, since some of the cloud would initially remain close to the ground, but the general pattern of a maximum at a distance from the source is valid, provided the particles are small.

These figures have the same horizontal distance scale used for the cold release, however, the dosage scale has been decreased by two orders of magnitude (10^1). Calculations for a daytime hot release involving wind speeds of 2 meters per second or less have not been performed, as the occurrence of such wind speeds at the calculated rise height of 860 meters would be rare. Figure 2.6 combines both the 1 meter per second and 2 meters per second nighttime patterns; the isopleths for night conditions of ≤ 3/8 cloudiness are off of the graph, since they would theoretically begin beyond 100 kilometers and, as discussed before this, would be unrealistic. The fact that the distance between the source and the first ground dosages in night cases 6 meters per second or greater (fig. 2.8 and 2.9) is less than some of the day isopleths, is due to the different cloud rise heights employed in the calculations (day, 860 m.; night, 400 m.). The effects of insolation, cloudiness, and wind speed discussed for the cold release are also in evidence here. Of greatest importance, however, is the fact that only in the 4 meters per second category (fig. 2.7) does the dosage get above the suggested harmful limit of 10 units; and then the extreme case reaches a value of only 26 units for a distance on the order of 2 kilometers and maintains a value of at least 11 units for a distance of 11 kilometers. Thus

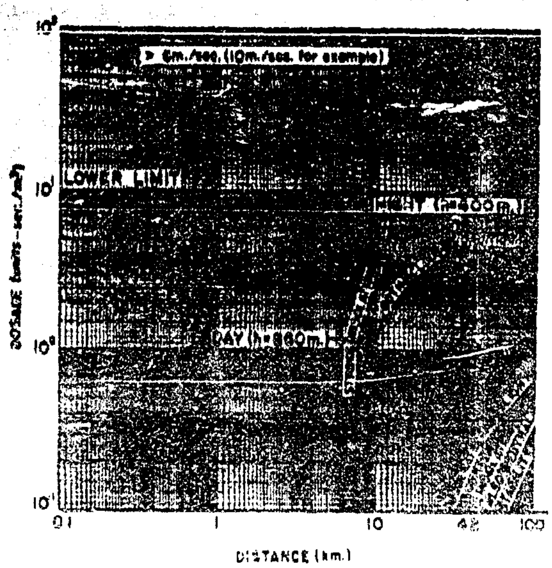

Figure 2.9. Downwind Centerline Dosages, Hot Cloud Aloft, Wind Speed, >6m./sec.(10m./sec. for example).

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for all practical considerations, the hot release can be discounted from a potential hazard analysis.

2.2.3 Cloud Width

Figures 2.1 through 2.5 show the ground conditions along the cloud centerline. Obviously, the width of the cloud must be defined, if its true relation to the contaminated area is to be evaluated. This has been accomplished in figures 2.10 through 2.13 for the cold release by computing dosage isolines of 400, 90, and 10 dosage units. Let us arbitrarily say that a dosage of 400 units per cubic meter represents the lower limit for a lethal dose; between 400 and 90 illness is likely; between 90 and 10 injury is unlikely but some expense may be incurred; and below 10 no injury or expense is contemplated [23, 29]. To facilitate comparison, the same scale has been used for both axial and cross-axial distances and for all patterns; this, due to space limitations, has necessitated a chopped off appearance (at 42 km.) for the night patterns; however, as previously discussed this is more in keeping with reality. As a gross comparison the numerical axial concentration distance limits, for any of the three categories (400, 90, 10) that extend beyond 42 kilometers, are included on figures 2.12 and 2.13. These horizontal plots emphasize the differences in diffusion areas represented by day and night, insolation or cloudiness, and wind speed. The lateral limit of significant dosages (≥10 units), in most cases, does not exceed 6 kilometers (3 x 3 km.) and of lethal dosages (400 units), 3 kilometers (2 x 1.5 km.).

No similar calculations have been made for the corresponding hot release, for the obvious reason that the dosages derived therefrom are, in most cases, not significant.

2.3 Deposition from the Cloud

2.3.1 General Considerations

The diffusion studies have provided a basis for evaluating the direct effects of the cloud as it passes over the countryside, but they give no indication of the particular residue that may be transferred to ground surfaces, vegetation, and buildings. The term "transferred" is used initially to suggest the lack of knowledge concerning the physical processes actually involved. The question of what occurs at the boundary of interaction between an aerosol cloud and the underlying ground surface is clearly a very complicated one. Material is deposited on surfaces by a variety of physical processes, few of which are well understood. Gravitational set-

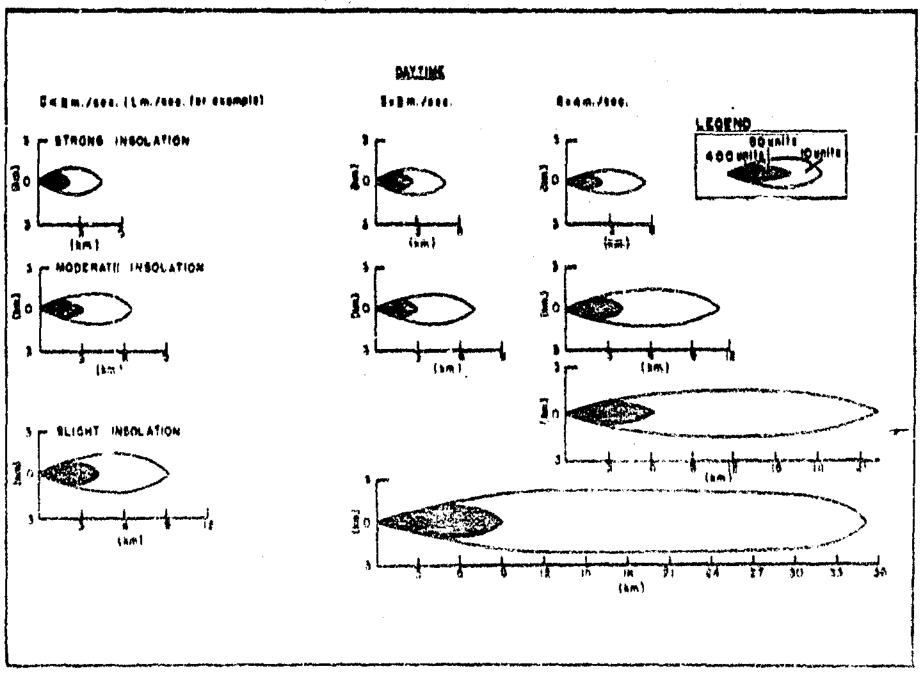

Figure 2.10. Cloud Width — Isopleths of a Contaminant, Ground Level Cloud, Daytime, Wind Speeds: <2m./sec. (1m./sec. for example), 2m./sec., and 4m./sec.

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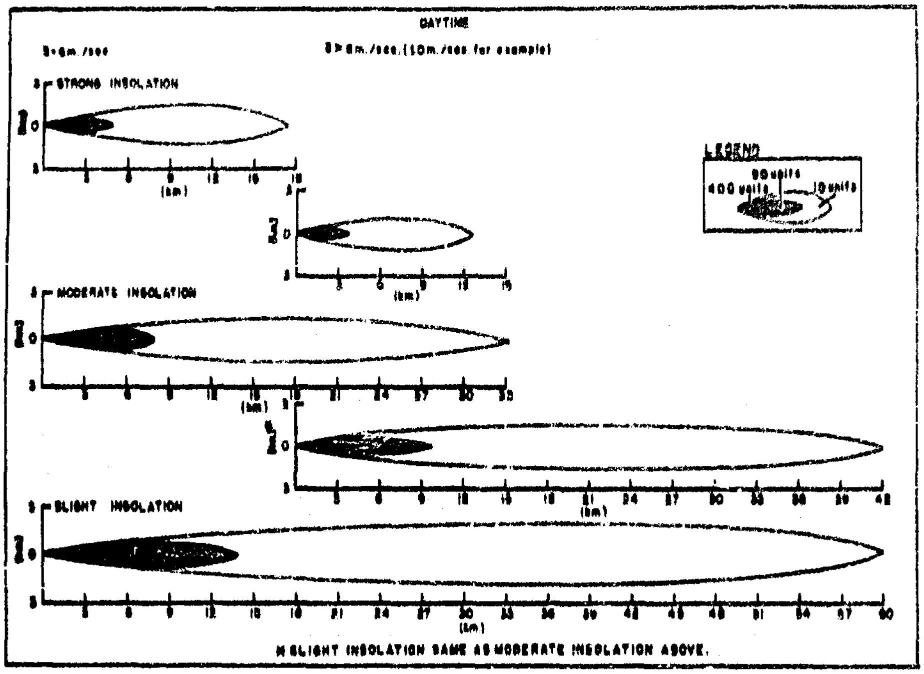

Figure 2.11. Cloud Width - Isopleths of a Contaminant, Ground Level Cloud, Daytime, Wind Speeds: 6m./sec. and >6m./sec.(10m./sec. for example).

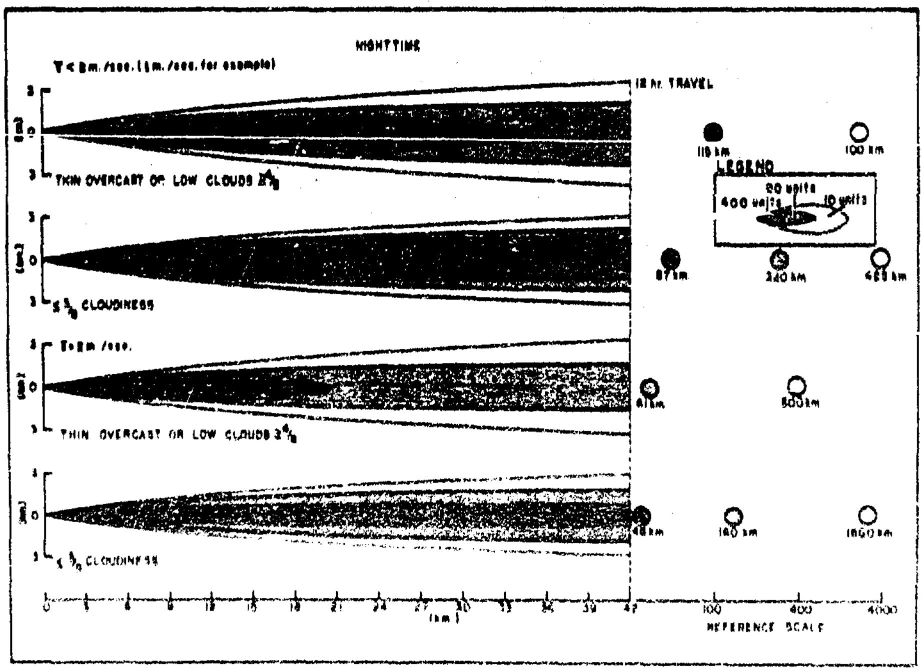

Figure 2.12. Cloud Width - Isopleths of a Contaminant, Ground Level Cloud, Nighttime, Wind Speeds: <2m./sec. (1m./sec. for example) and 2m./sec.

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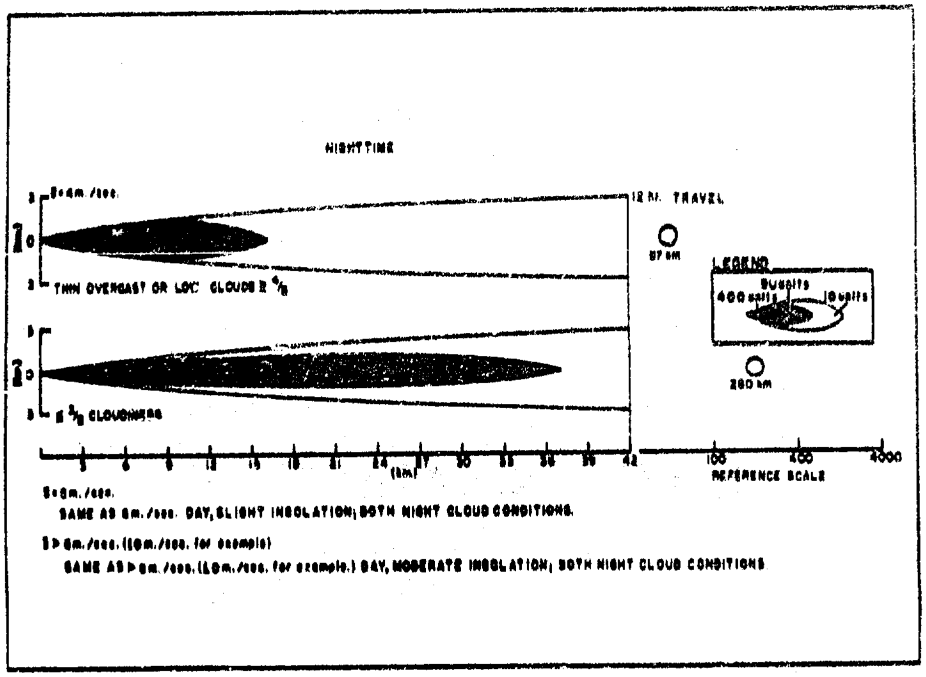

Figure 2.13. Cloud Width - Isopleths of a Contaminant, Ground Level Cloud, Nighttime, Wind Speeds: 4m./sec., 6m./sec., and >6m./sec.(10m./sec. for example).

tling, adsorption, particle interaction, molecular and turbulent diffusion, and various chemical and electrostatic effects no doubt must be considered. Ranz and Johnstone [15] have shown that impaction, electrostatic, and thermal forces may be equally important for 1μ particles, which are of importance in this particular study. Similarly, a simple treatment probably does not describe scavenging by rain, in which the hydroscopic nature of the particles may be as important as the size and shape. Forms of precipitation other than rain presents even more complicated problems.

Unfortunately, scientific knowledge of the right type for this study is even more inadequate than that applying to diffusion. The main reason is that complete field experiments in deposition and rainout are extremely difficult to conduct, and there has been little need for them until recent years. Theoretical work and most laboratory studies have dealt with idealized spherical particles under conditions very different from those in the atmosphere. Field experience is not sufficiently complete to have an important influence on this analysis. For these reasons, it seems best to utilize simple approximations for such effects rather than to become involved in a complex treatment which may not fit the facts any better.

The first problem is to establish a physical description of the particles. It seems most probable that a pollutant release would occur as a result of or in combination with combustion, with the particles having the general characteristics of a fume. The size distribution fitting this description would involve very small particles. However, the possibility cannot be ruled out that a much larger particle size distribution could be caused by a pollutant release of a different nature or by unknown processes.

A straightforward approach to deposition, presented by Chamberlain [4] and well suited to the study, is used without alteration. The calculations have been performed for only two special cases of deposition, washout and total instantaneous washout. For most of the particle sizes assumed here, dry deposition, that is deposition during non-precipitating conditions due to gravitudinal settling and impaction, would

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be negligible. In a case of larger particles, however, the patterns computed for washout could serve as a guide to the *orders* of magnitude involved, and according to Gifford [9] maximum dry deposition would be one order of magnitude smaller than total instantaneous washout.

2.3.2 Washout

To account for the cloud depletion from washout, that is removal of cloud material by rainfall, Chamberlain introduced the exponential factor $e^{-\Lambda t}$ in the numerator of the Gaussian dispersion formula. It is reasoned that since rain removes material from the whole cloud depth, the process can be likened to radioactive decay, because the entire cloud is affected uniformly rather than preferentially near the ground, and the shape of the cloud-distribution function is not altered; thus, rain modifies and decreases dispersion distances by the above exponential factor.

The x and the t in the exponential have been previously identified, the Λ is known as the washout coefficient and is mainly related to rainfall rate and particle size; a figure of 1×10^{-4} has been used in this investigation and represent rainfall of the order of 0.1 inches per hour and particle sizes of the order of 1 to 3 microns.

A proper description of natural rainfall would reflect its inconstant nature, for it is almost certain that for any given period a rapidly varying rate would be found. Therefore, sharp departures above and below the washout curves should be expected in an actual case. Heavier rainfall rates would have the effect of increasing deposition close to the source, but decreasing it further away because of more rapid depletion of the total available pollutant.

(a) Modification of Diffusion Curves

Figures 2.14 and 2.15 show the changes which can occur in dosage rates due to depletion of the cloud by the exponential term characterizing the washout process. Only two wind speeds are presented, 1 meter per second and 10 meters per second, the heavy lines are the curves corrected for deposition and the thin lines represent uncorrected dosages and are similar to curves presented in figures 2.1 and 2.5. The figures show that washout is much more effective as wind speed decreases and stability increases.

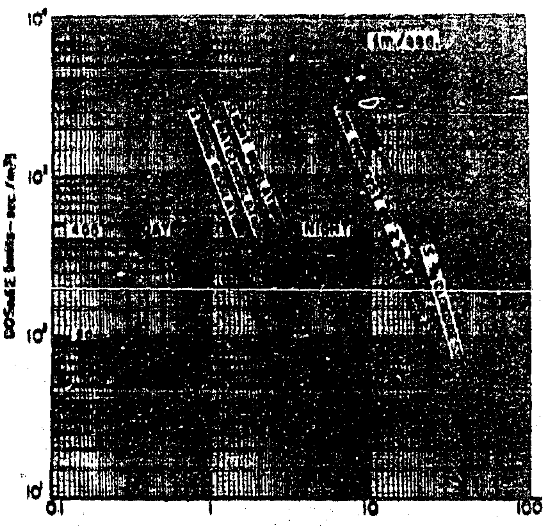

Figure 2.14. Downwind Centerline Dosages, Ground Level Cloud, Corrected for Washout, Wind Speed <2m./sec.(1m./sec., for example).

(b) Pollutant Deposited [10]

The amount of pollutant deposited by washout is obtained by integrating the diffusion equation containing the washout term, with respect to height; for centerline deposition this yields,

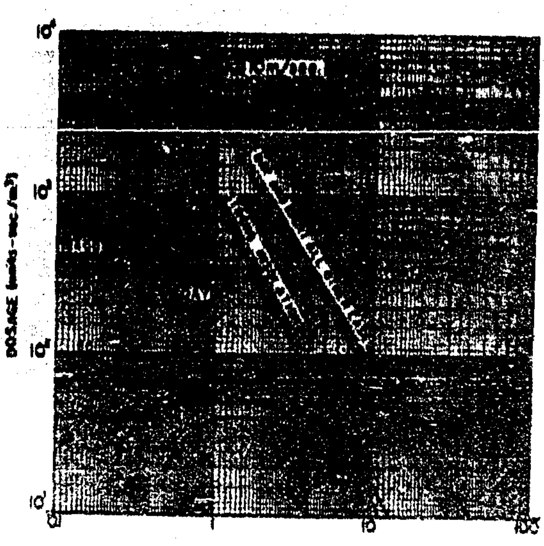

Figure 2.15. Downwind Centerline Dosages, Ground Level Cloud, Corrected for Washout, Wind Speed >6m./sec.(10m./sec., for example).

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$$w_{(1)} = \frac{Q \Lambda e^{-\frac{\Lambda x}{\bar{u}}}}{(2\pi)^{1/2} \sigma_1 \bar{u}} \cdot \qquad (2.2)$$

Certain implications of this equation are very important. The vectical diffusion parameter (σ_1) disappears from the equation in the same way that λ does. No advantage is gained from the rise of a hot cloud; therefore, all releases are effectively treated as cold. The rise of the hot cloud is no longer as helpful in lessening pollution concentrations (compared to the surface cold cloud) as it had been in cases of diffusion; in fact, the highest deposition rates at great distances are now found with the fast-moving clouds aloft (fig. 2.16).

Figure 2.16 represents cold cloud centerline deposition in terms of units per square meter for wind speeds ranging from 1 meter per second to 10 meters per second. The curves were computed using the above equation assuming neutral stability, a condition common during overcast and rainy days or nights. Note that the curves do indicate possible serious ground-level deposition (the suggested range for some contaminants is from greater than 2×10^{-1} units per square meter, where evacuation within 12 hours is necessary, to less than 10^{-4} units per square meter, where no expense is contemplated (24]) and that the higher speed isopleths cross the lower speed isopleths as distance increases.

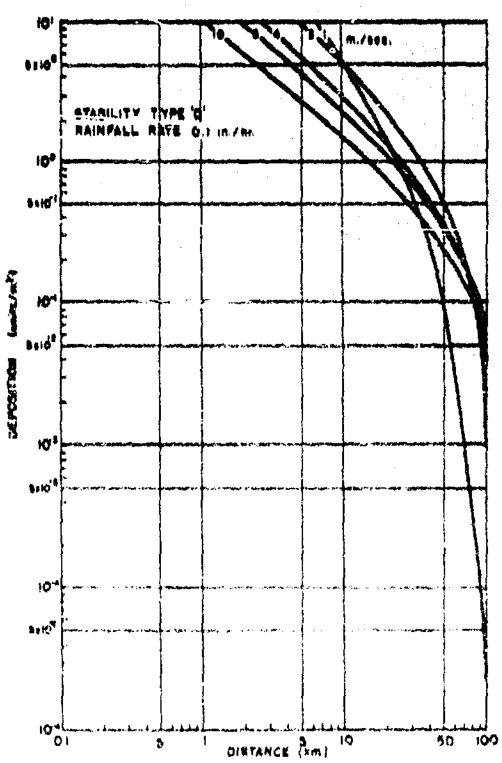

Figure 2.16. Downwind Centerline Deposition (units/m.²) from Rain, Ground Level or Cloud Aloft.

(c) Total Instantaneous Washout [10, 23, 25]

Total instantaneous deposition is the limiting case of the complete deposition of an entire cloud or plume of an air-borne material, such as the highly improbable occurrence of a cloud under a sudden heavy rain shower. The following equation depicts the situation,

$$w_{(1)} = \frac{Q}{(2\pi)^{1/2} \sigma_1 \bar{u}} \cdot \qquad (2.3)$$

Figure 2.17 is derived from the equation; since intense showery precipitation is due to pronounced instability, atmosphere stability criteria A (see table 1.1) has been used for the solution; also, because of associated increased wind speeds, the wind speeds have been chosen to be 4 meters per second or greater. As can be seen from figure 2.17, the isopleths for these conditions do not cross, and significant deposition values extend from the source to 100 kilometers.

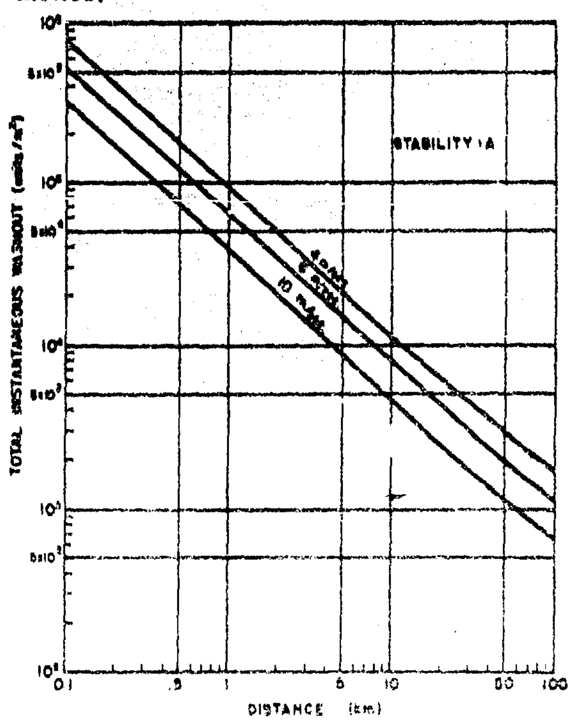

Figure 2.17. Downwind Centerline Deposition (units/m.²) from Total Instantaneous Washout, Ground Level or Cloud Aloft.

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3. CLIMATOLOGY OF THE HAMPTON ROADS AREA

3.1 Location and Topography

Hampton Roads, one of the largest natural harbor areas in the world, is the name given to the nearly enclosed body of water formed by the confluence of the James, Nansemond, Elizabeth, and Lafayette Rivers, prior to emptying to the east-northeast into Chesapeake Bay. Norfolk and Portsmouth, Virginia are located on the east and southeast sides of the area, and Newport News and Hampton, Virginia are on the northwest and north sides, (see figure 3.1). Docking facilities are located in various areas of the port. The Norfolk Naval Station piers are located on the eastern side of the harbor and extend from Sewell's Point to the mouth of the Lafayette River. Ships of different types and sizes (among which are submarines, destroyers, cruisers, and carriers as large as the nuclear-powered Enterprise) may be berthed here. Often vessels may also be found at anchor in the Roads proper. Another possible ship location, the Newport News Shipbuilding and Drydock Company, is located on the northwestern side of the Roads, in the city of Newport News. Included in the Hampton Roads Area for the purposes of this study are the ship docking facilities along the Elizabeth River from Lambert's Point to the Norfolk Naval Shipyard via the Southern Branch of the Elizabeth River.

The northeast, and southeast sides of Hampton Roads contain the larger population centers, whereas the western and adjacent southern sides are relatively sparsely populated. The most densely populated sections in the area are located southeast of the Roads along the Southern and Eastern Branches of the Elizabeth River. This river separates Portsmouth, Norfolk, and Chesapeake from each other.

The topography of the region is low and flat; as an example, the elevation above mean sea level of Norfolk Naval Air Station is 15 feet. To the southwest of the region lies the Dismal Swamp, which extends into North Carolina. As one goes westward the terrain slopes imperceptibly upwards to a distance approximately 150 miles west of the area; here the land rises sharply into the Appalachians, with elevations averaging 3,000 to 4,000 feet above mean sea level. Man has not altered the region's topography in any marked manner, as very few buildings even approach 100 feet; the taller structures are located in the southwestern part of the city of Norfolk.

3.2 General Climate

The Hampton Roads area (approximately 36.8° N. and 76.4° W.), located in mid-latitudes on the east coast of a continent, has a climate which is temperate, rainy without a dry season, and has warm summers. In addition, winters are usually mild since the circulation of a cold air mass moving towards the area will usually have a trajectory over the warmer ocean waters within 24 to 48 hours. Figure 3.2 presents the monthly temperatures, extremes of temperature, and monthly precipitation for Norfolk Municipal Airport (ORF).

The *mean* position of the unoccluded polar front lies to the southeast of the area. Being situated in midlatitudes, there is considerable variation in wind direction and speed, both aloft and at the surface. The *prevailing wind* has a steadiness of only 16 percent and, on the average, blows from the north during the cold season and the southwest during the warm season.

The weather encountered in the area results almost exclusively from two air masses and the front which divides them, being alternatively influenced by polar continental (cP) and maritime tropical (mT) air, with the transition being heralded by the passage of the polar front. In the winter season frontal activity in the area is pronounced, while in summer the area is frequently a region of frontolysis (front decaying), in which fronts which were well defined in the eastern continental United States become extremely diffuse and are difficult to locate and forecast accurately. The flow, in summer, is generally governed by the western extension of the Bermuda semipermanent high pressure cell. During the transition seasons, spring and fall, the polar front is often quasi-stationary and oriented east-west, either just north or just south of the region. Stations to the north of the front will usually experience fog, stratus, drizzle, or rain; whereas stations to the south will generally be clear. Forecasting the location of the front is difficult, for the front may have a north-south oscillation ranging from a few miles to a few hundred miles; in many cases, a station in the path of these oscillations will experience repeated clearing and clouding over in the same day. To the southeast of the area lies the well-

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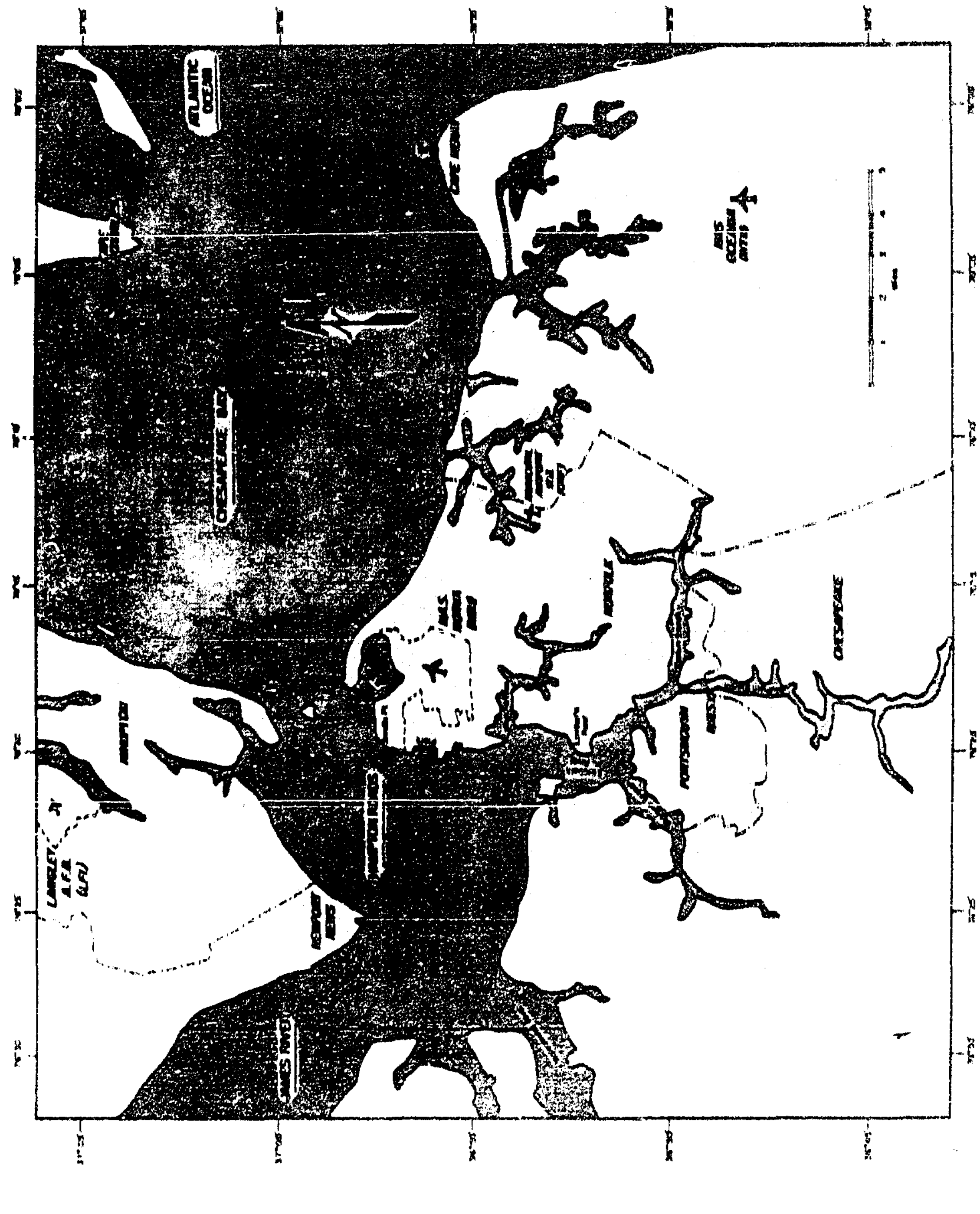

Figure 3.1. Geographical Location Map.

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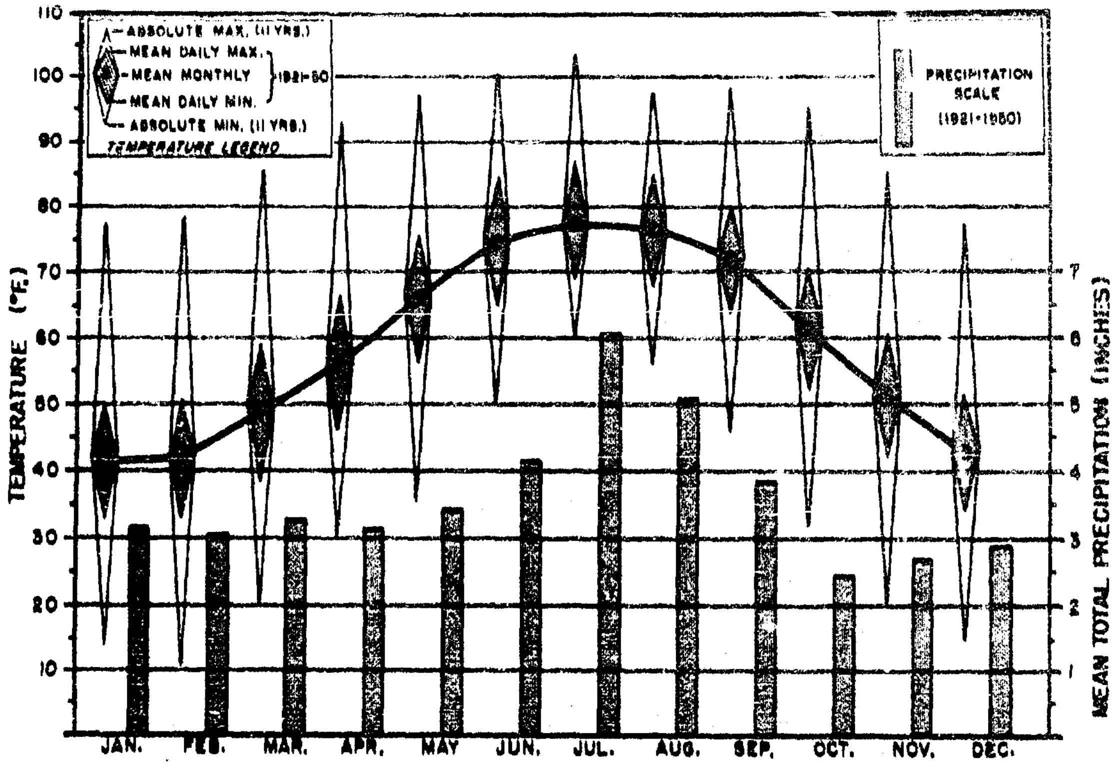

Figure 3.2. Annual Variation of Monthly Temperatures and Precipitation for Norfolk, Va. (ORF).

known cyclogenesis region, in which the not-infrequent *Hatteras low* is spawned.

The Hampton Roads region can be influenced by hurricanes, with July normally marking the beginning of the hurricane season. However, it is usually the middle of August before the probability of hurricane occurrence in this region reaches a point of concern. These destructive storms usually develop north of the Lesser Antilles and move erratically along the Gulf Stream current, September is the month with most hurricanes; the official hurricane season ends on November 15th.

3.3 Dispersion Climatology

3.3.1 Wind Structure

In the study of dispersion wind structure is important, for it not only determines *how fast* a pollutant will be dispersed but also *where* it will be dispersed to. Figures 3.3 through 3.9 represent wind roses for five stations in the Hampton Roads area drawn on a base chart of the region. The wind breakdown proceeds from an annual presentation to a seasonal and finally to a monthly presentation; day (0800-1900 EST) and night (1900-0700 EST) wind roses are shown for each grouping. In general the five stations show similar wind regimes; Cape Henry, being a cape location in the transition zone between bay and ocean, shows the most departure from the other stations; Oceana, being closer to the open ocean, also shows some departure.

A look at the annual, day wind roses (fig. 3.3) will show the east coast, middle-latitude character of this region. A *prevailing wind* calculation on an annual basis is less meaningful than on a seasonal or monthly basis; however, the warm season influence of the western extension of the *Bermuda high* is evident, as the frequency of southwest winds is somewhat higher than the general distribution. Frequencies of north through northeast winds are also somewhat higher due, in part, to the circulation of the offshore, north-northeast

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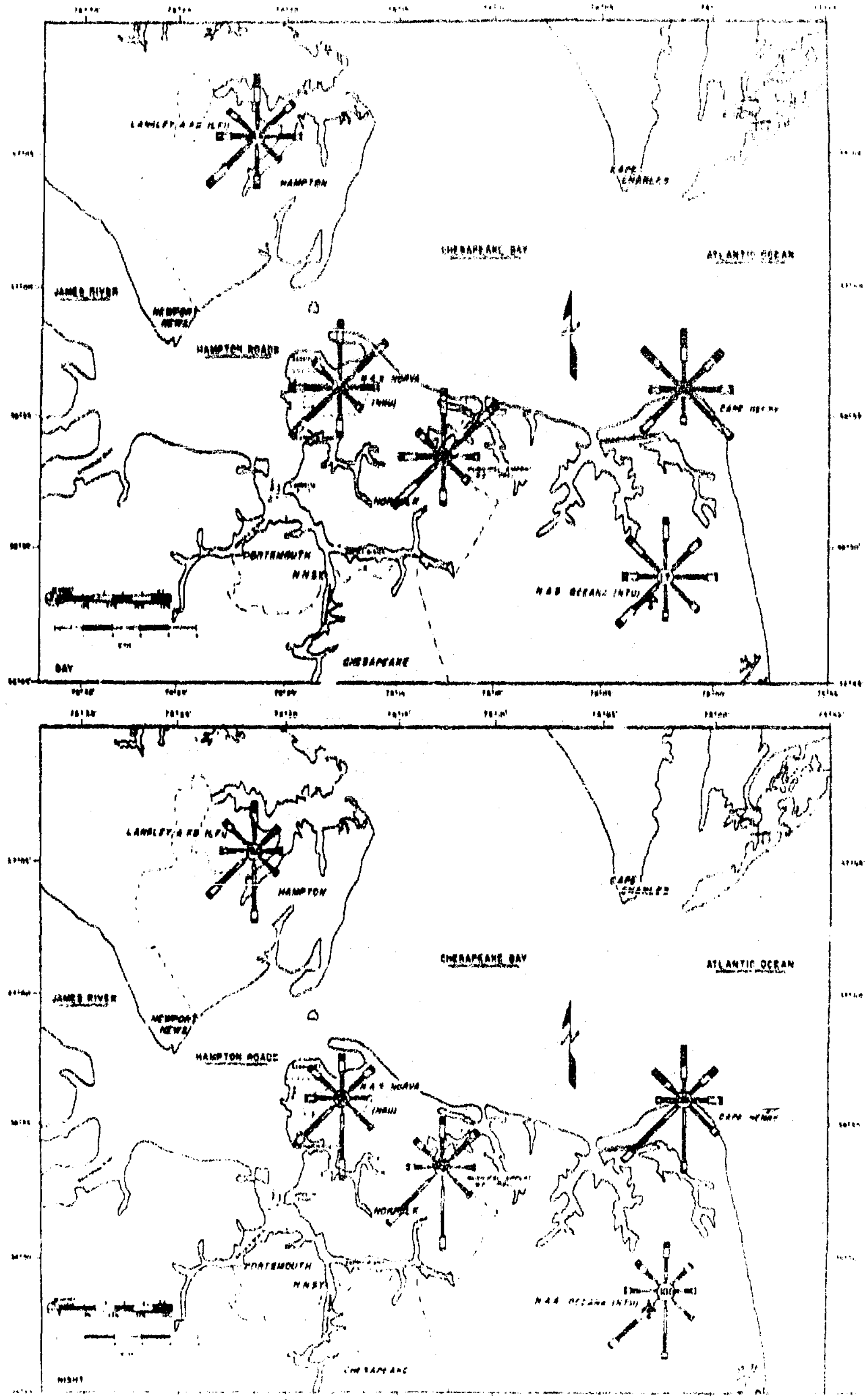

Figure 5.4. Annual Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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moving, *Hatteras lows* and afternoon warm-season sea breezes. The least prevalent wind direction is from the southeast; with the exception of Cape Henry, for which a southeast wind is the most frequent. Oceana shows the most uniform annual wind distribution of all the stations. Annual day wind speeds average 11 knots at Cape Henry and 10 knots at the remaining locations. Although strong winds are possible from any direction, northwest winds (when they occur) tend to be strong and gusty.

The night annual wind roses (fig. 3.3), in contrast to the day roses, do show that the prevailing wind directions at all stations are south through southwest. This direction preference is a result of the already discussed *Bermuda high* and a night land breeze which flows toward the relatively warmer waters of Chesapeake Bay. The other wind directions are relatively uncommon, with an east wind being the most uncommon. Wind speeds at night are, on the average, 3 knots less than during the day, with Cape Henry showing the least diurnal change. Langley AFB has the highest frequency of calms (18.0%) and Cape Henry the lowest (0.0%).

(a) Winter (December, January, February)

The day, winter wind regime (fig. 3.4) shows the influence of the increased frequency of frontal passages — winds from the southwest through north directions prevail, with a north wind being the most prevalent. Winds from an east or southeast direction are noticeably absent. The winter, night roses (fig. 3.4) indicate some diurnal changes in wind direction, as north winds decrease in frequency and south winds increase. Langley AFB shows the least diurnal wind directional change. Its diurnal variation is due mainly to a significant drop-off in wind speed.

The waning influence of the *Bermuda high* is evident during the daytime in December (fig. 3.5) for the three stations closest to Hampton Roads (LFI, NGU, ORF), as southwest winds are still common. One would expect northwest winds to be more prevalent than indicated during this time of year, when cold front passages become more numerous; however, it appears that the Hampton Roads region, in December, is far enough south of the track of *lows* associated with cold air outbreaks, so that post cold-frontal isobars begin assuming anticyclonic curvature in this region. The typical northwest wind, which usually follows cold fronts, is thus veered to the more frequently indicated north wind. Cape Henry and Oceana, although showing some of the above singularities, present a more uniform southwest through north distribution. As in the winter distributions, the frequency of winds with an easterly component is small. The diurnal changes in evidence for winter, may also be seen in the December nighttime wind roses (fig. 3.5). Other differences are also noticeable, mainly a nighttime decrease in west winds, and for the three Roads neighboring stations, an increase in northwest winds. A nighttime increase in southwest winds at Cape Henry and Oceana is also perceivable. December wind speeds are somewhat less than the two other winter months, and average 9 knots; the average diurnal wind speed decrease is on the order of 1 knot. Cape Henry shows the singularity of having higher average wind speeds at night than in the day (12 knots vs. 11 knots).

In January (fig. 3.6), the daytime southwest wind is not as frequent as in December (except Cape Henry). As the storm track in midwinter becomes displaced further southward, this region comes more and more under the influence of northwest cyclonic flow following the passage of a cold front. Evidences of this can be seen in the increasing frequency of northwest winds which occurs between December and January. In addition to east winds, south winds also become rare in January. A look at the January night wind regime (fig. 3.6) shows a noticeable nightly increase in south winds at all stations. Easterly winds, as in the daytime, are infrequent. January wind speeds are higher than December's, and average 10 knots; the diurnal wind speed change is small and for Cape Henry is nonexistent.

February finds the polar front south of the Hampton Roads region, and in a position to favor east coast cyclogenesis. These offshore developments are responsible for the increase in north through northeast winds as seen in figure 3.7, which depicts the February wind distribution. The wind roses for this last month of winter show a more uniform distribution than the two previous winter months. As in the seasonal winter roses, winds from the southeast are rare in the immediate vicinity of Hampton Roads. Northwest winds at Oceana and Cape Henry are generally stronger and more frequent than at the other stations. In February diurnal wind changes (fig. 3.7) are the smallest of the winter months and consist essentially of a nightly increase in south winds. Wind speeds in February are, in general, similar to those of

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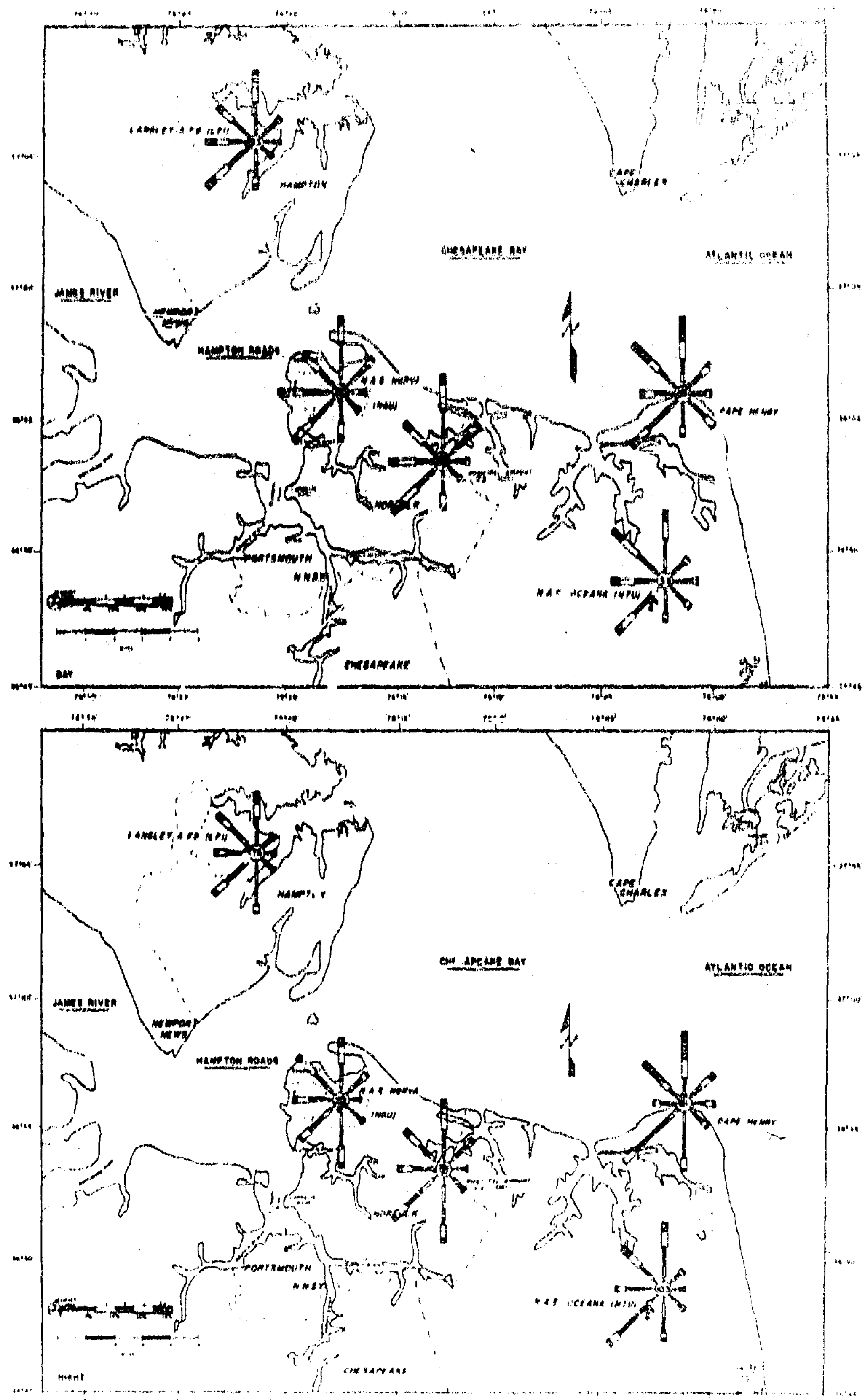

Figure 14. Winter Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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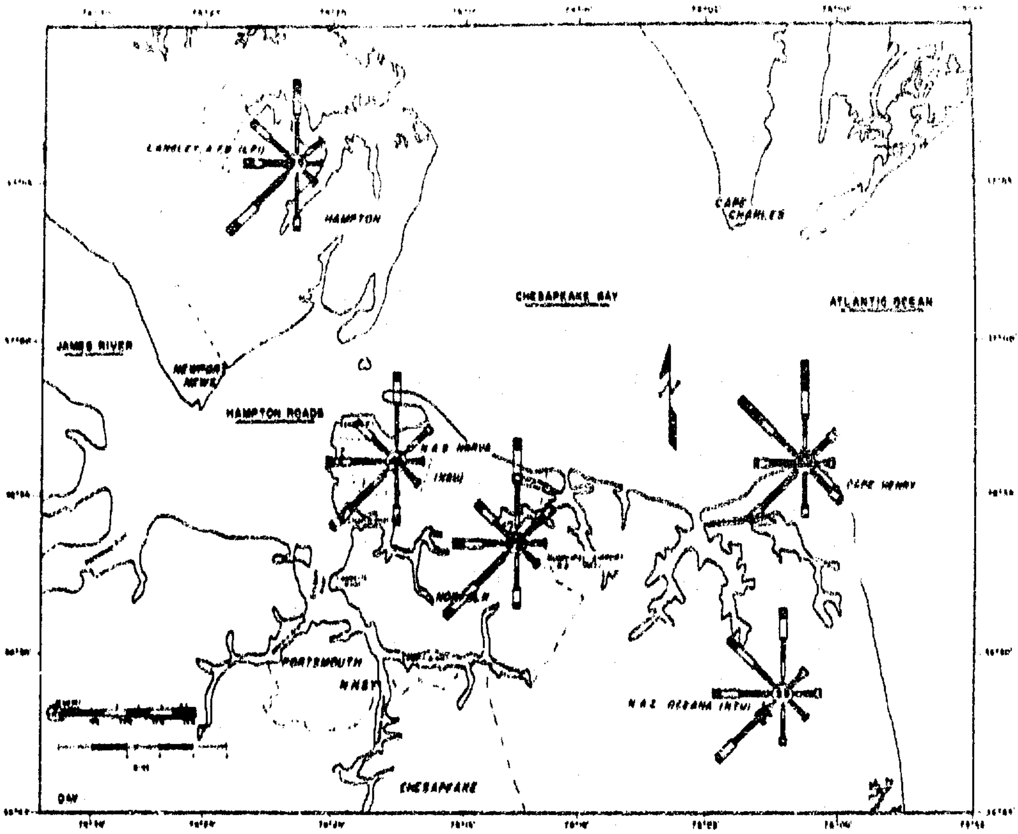

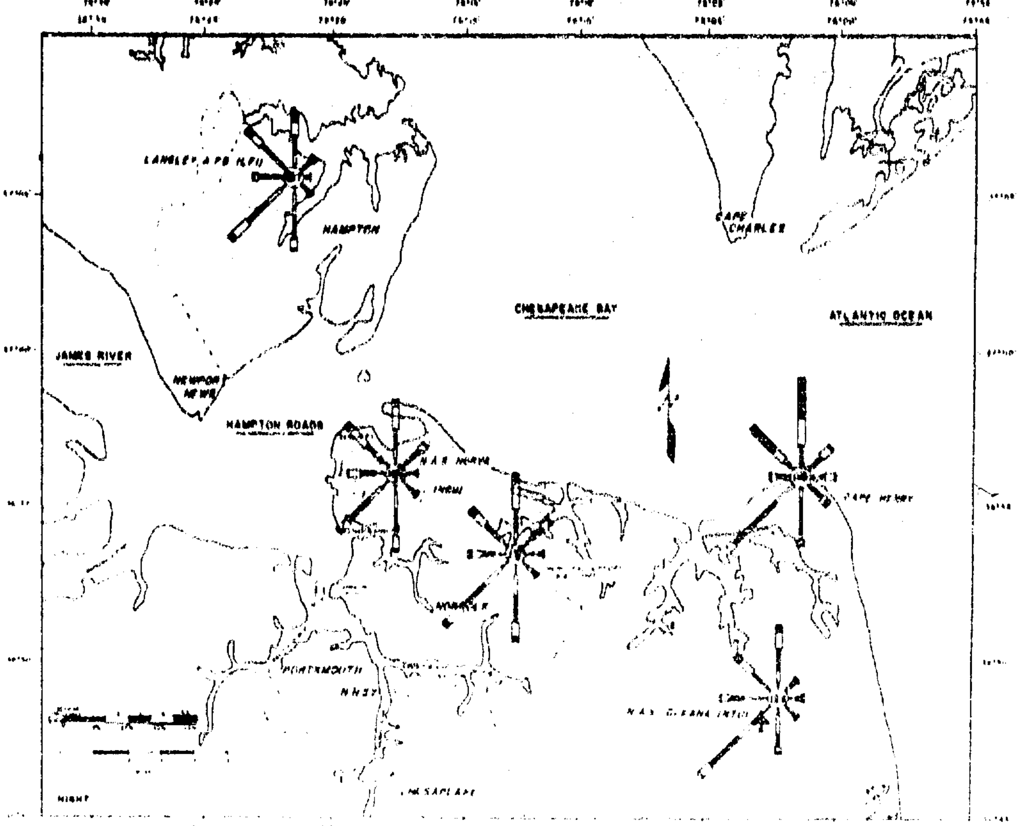

Figure 3.5. December Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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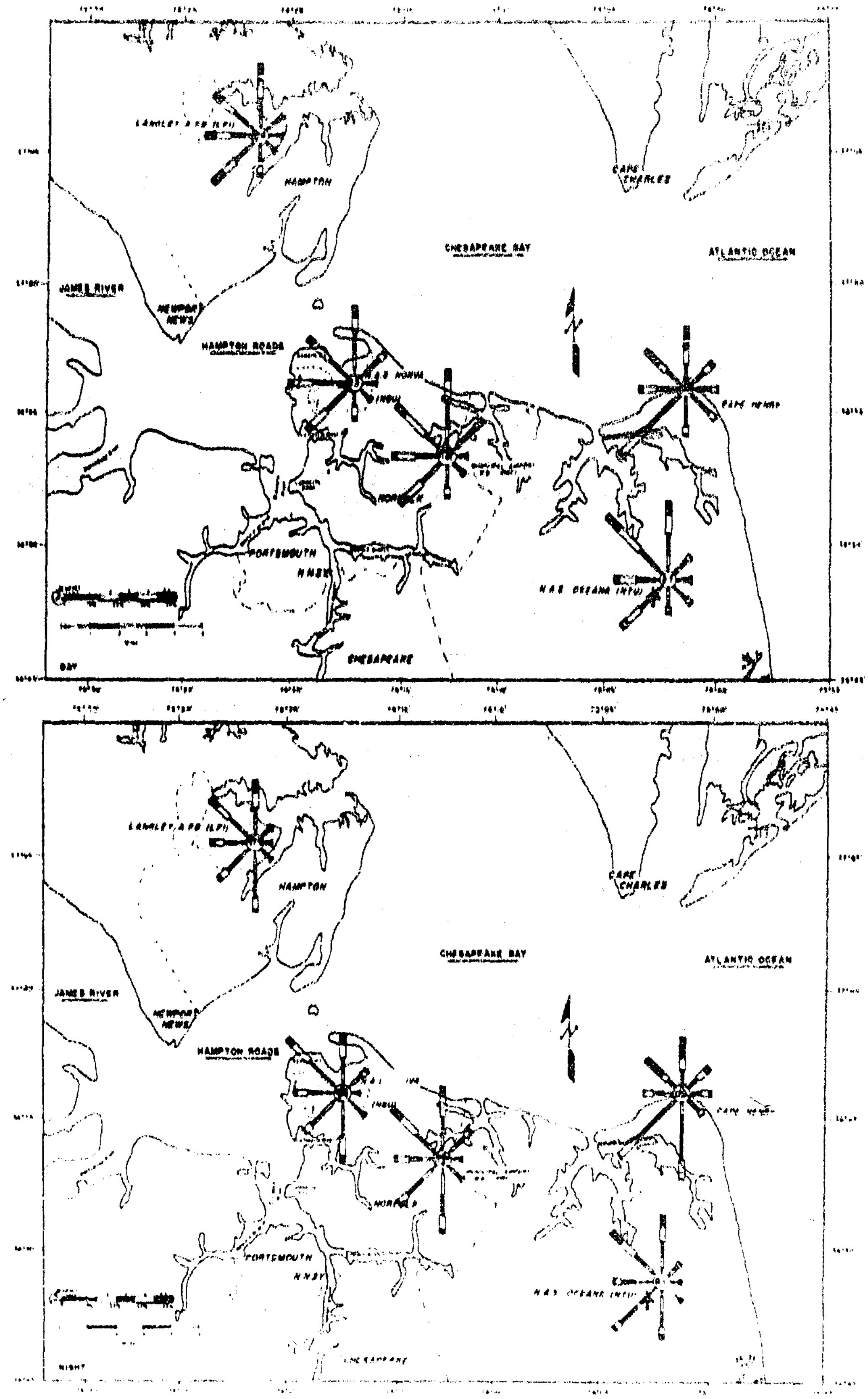

Figure 3.6. January Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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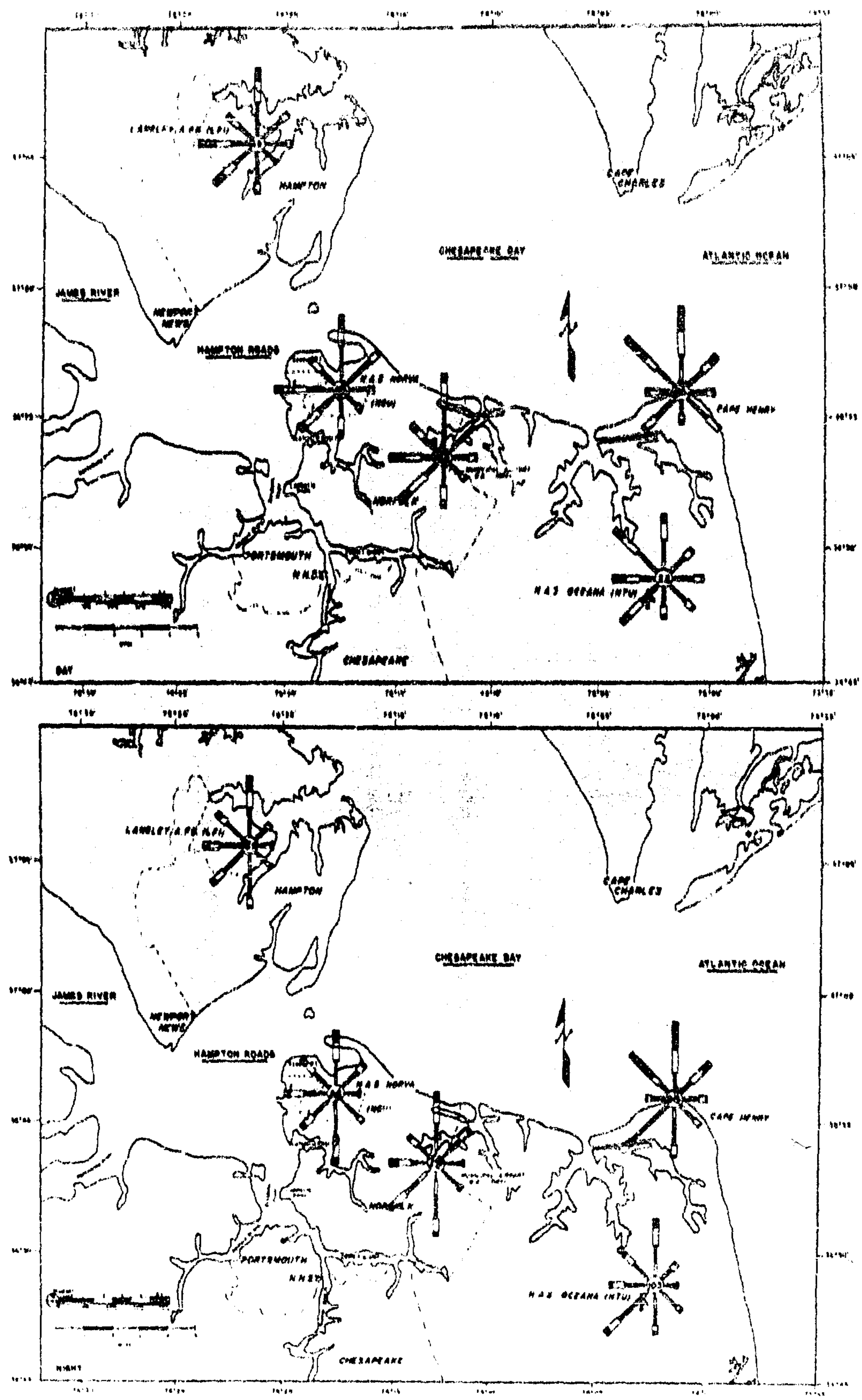

Figure 3.7. February Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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January.

(b) Spring (March, April, May)

Since spring marks the transition time between winter with its repeated cyclonic disturbances, and summer with its persistent *Bermuda high* the spring, day wind roses show fewer predominating directions than the winter roses (fig. 3.8). The northeasterly and easterly flow apparent in the figure is indicative of offshore northeasterly-moving *Hatteras lows* found in early spring, and anticyclonic flow resulting from being on the north side of an east-west orientated front in the latter part of spring. Also, towards the end of spring, southwest flow increases as the *Bermuda high* builds and extends itself into the east coast of the United States. The flow in the vicinity of Cape Henry departs from the above, as strong northwest through north and weak southeast winds are most prevalent. Oceana shows the most uniform distribution in terms of both wind speed and direction. Minor wind directions for the three stations closest to the Roads are northwest and southeast; a northwest wind, when it occurs, is usually stronger than winds from other directions. The least predominant wind directions for Oceana and Cape Henry differ from the other stations and are west and south. Figure 3.8 represents the nighttime spring winds; some departure from the more uniform day distribution may be seen. The most significant feature is the marked increase in weak southerly winds; it appears that a weak local circulation is established under a nighttime inversion, producing general southerly flow in the region. The tendency for northwest winds to increase or remain constant at night either indicates an absence of diurnal change whenever this area is under the influence of northwest flow, or a nighttime preference for the passage of northwest wind-producing cold fronts. Wind speeds are at their highest in spring and for the area average 11 to 12 knots during the day and 9 to 10 knots at night; calms also are at a minimum in spring.

March daytime winds are presented in figure 3.9. Winds from a southwest clockwise through northeast are well represented (except Cape Henry). The passage of cold fronts, still common in March, account for the frequency of northwest through north winds; northeast winds are due, to the already discussed, passage of offshore *lows* . Southeast winds, with the exception of Cape Henry, are at a minimum in both frequency and speed. Cape Henry has its maximum frequency in a weak southeast wind and quite strong northwest through north winds, and its minimum frequency from southerly winds. The nighttime regime is more uniform than the day distribution (fig. 3.9) and generally resembles the spring nighttime roses; the diurnal changes in March, however, are not as pronounced as those of its season. Both day and night wind speeds are at their yearly maximum in March. The diurnal decrease in wind speed is at a minimum, which, in part, accounts for the small diurnal wind directional changes in March winds.

The daytime winds of April (fig. 3.10) exhibit the rapid change from the cold season to the warm season which takes place during this month of the year. Southwest winds are on the increase and northwest winds on the decrease. The northeast winds of April are due more to anticyclonic flow around a *high* rather than the cyclonic flow of offshore *lows* . Oceana and Cape Henry show considerable departure from the other stations, with Oceana (as before) exhibiting more uniformity in wind distribution and Cape Henry indicating a southeast maximum and a south minimum. A limited sea breeze is in evidence at the Norfolk Naval Air Station (NGU) in April as the 1400 LST (the time of maximum heating) wind rose (not included as a figure) shows an increase over the 0800 to 1800 LST composite rose (fig. 3.10) in northeasterly winds. The proximity of the Air Station to the relatively colder waters of Chesapeake Bay is responsible for this development. It is doubtful, however, that this sea breeze often extends very far inland, as the Weather Bureau station at Municipal Airport does not show one. The main diurnal changes in April (fig. 3.10 night) is a reduction in the frequency of winds coming from the west clockwise to the east, and an increase in winds from the south. A land breeze is, also, somewhat in evidence at Norfolk Municipal and Cape Henry as the 0400 LST (near the time of maximum cooling) wind rose indicates a more frequent southwest wind than is evidenced in figure 3.10 (night), which is a composite of all night hours (1900-0700 LST). April, day wind speeds are similar to those of March, while the night wind speeds are slightly lower.

May, day wind roses (fig. 3.11) are characterized by the presence of a sea breeze at all stations; its orientation is easterly for Langley, Cape Henry, and Oceana, and northeasterly for the Air Station and Municipal Airport. South-

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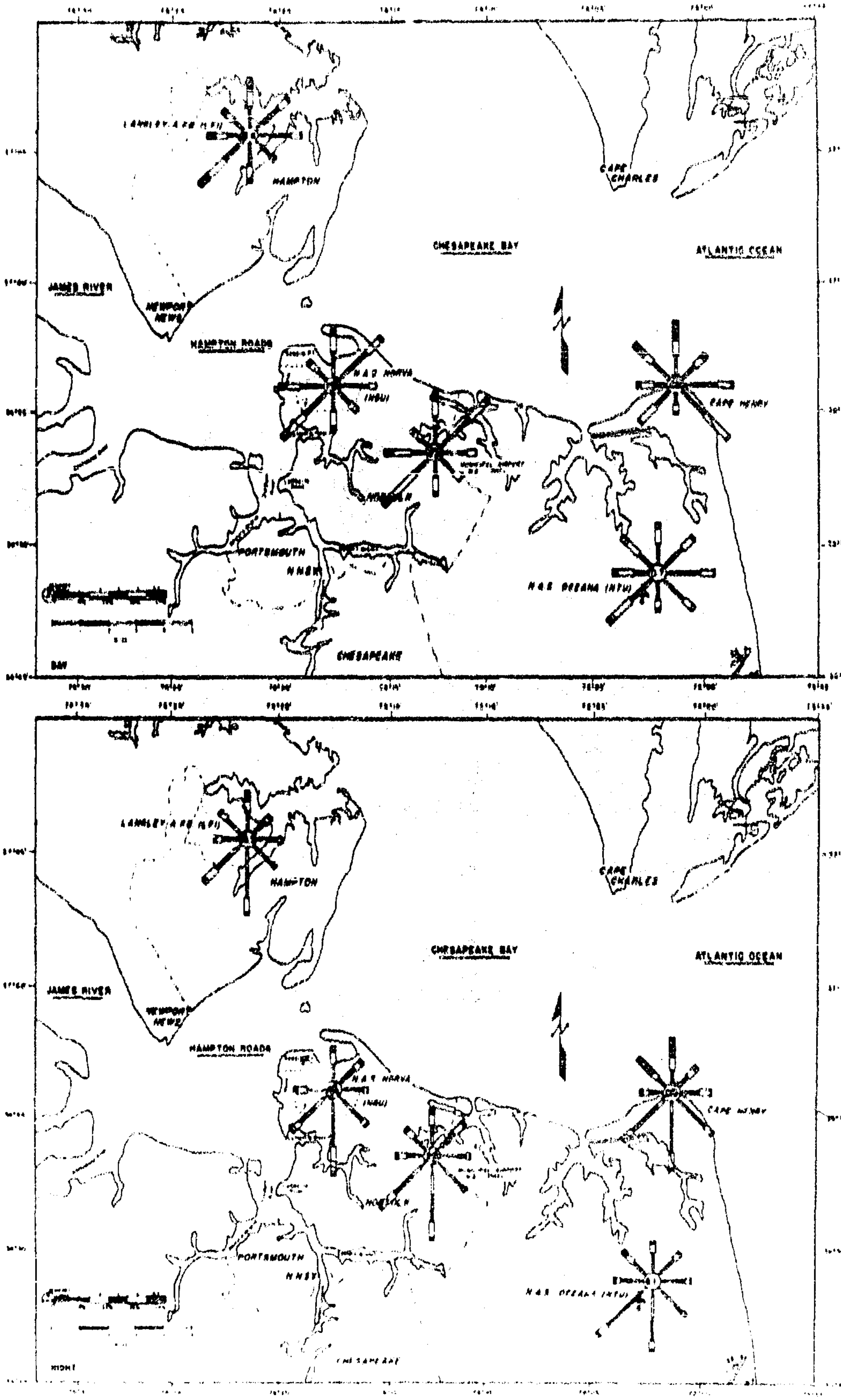

Figure 18. Spring: Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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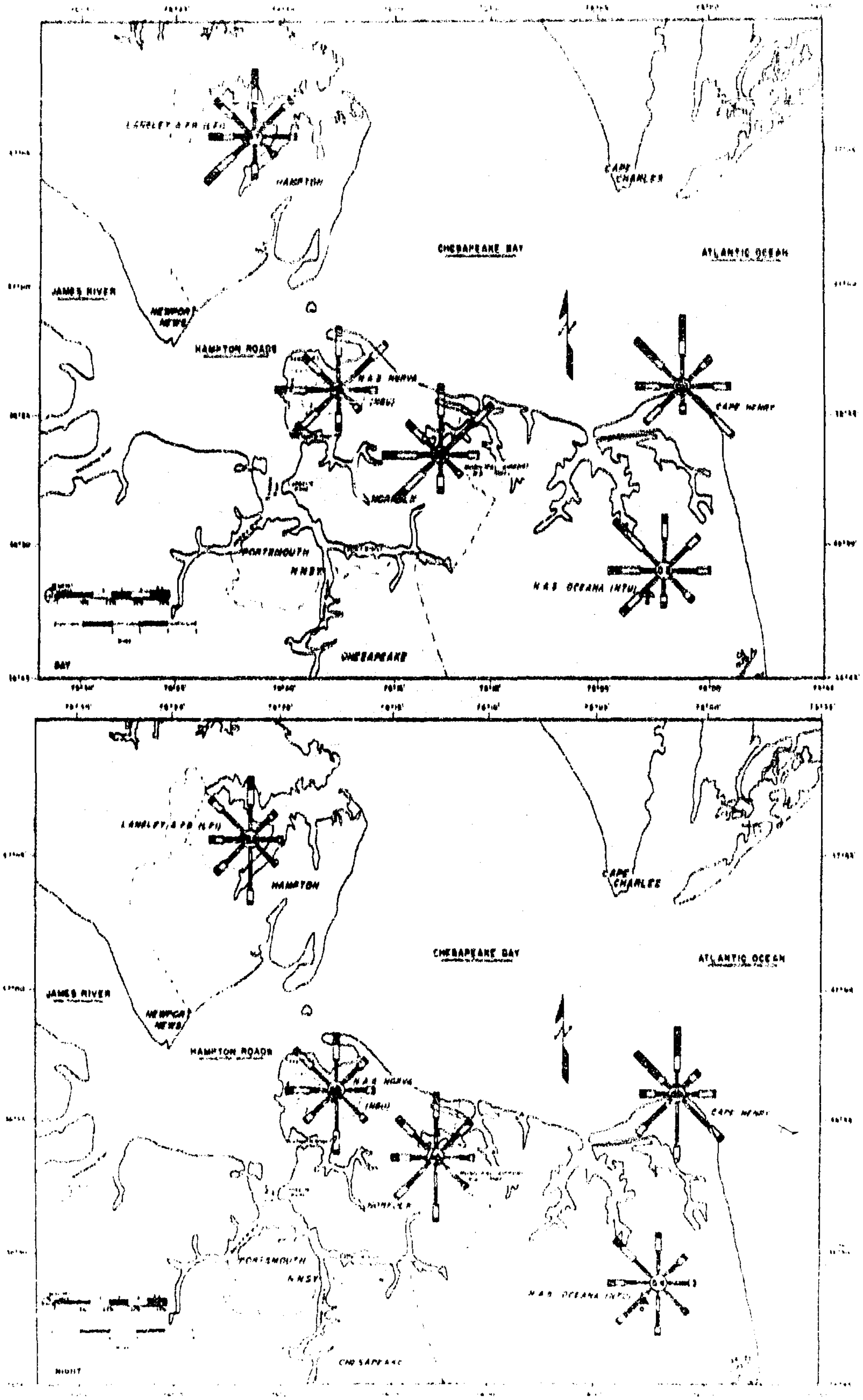

Figure 3.9. March Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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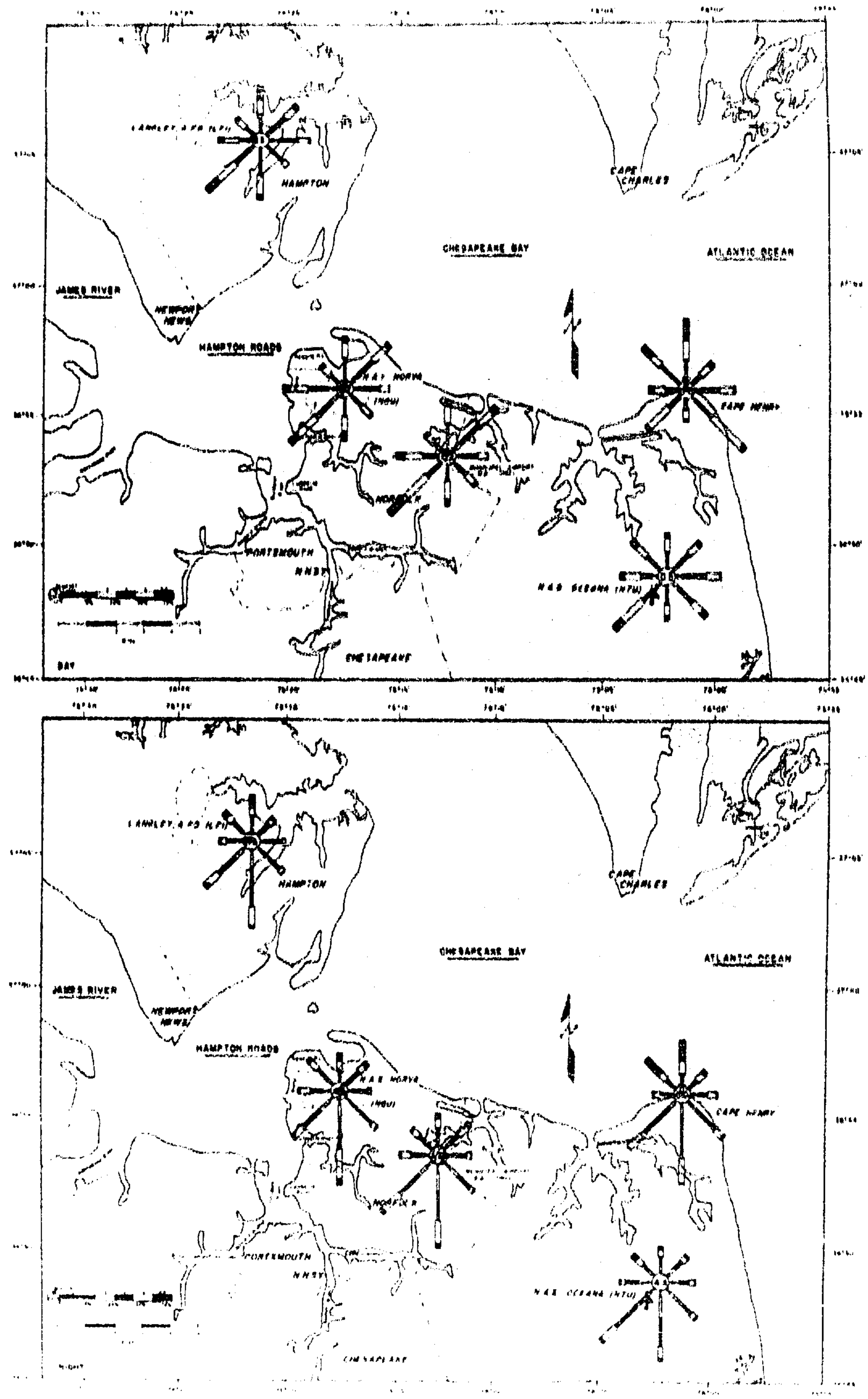

Figure 3.10. April Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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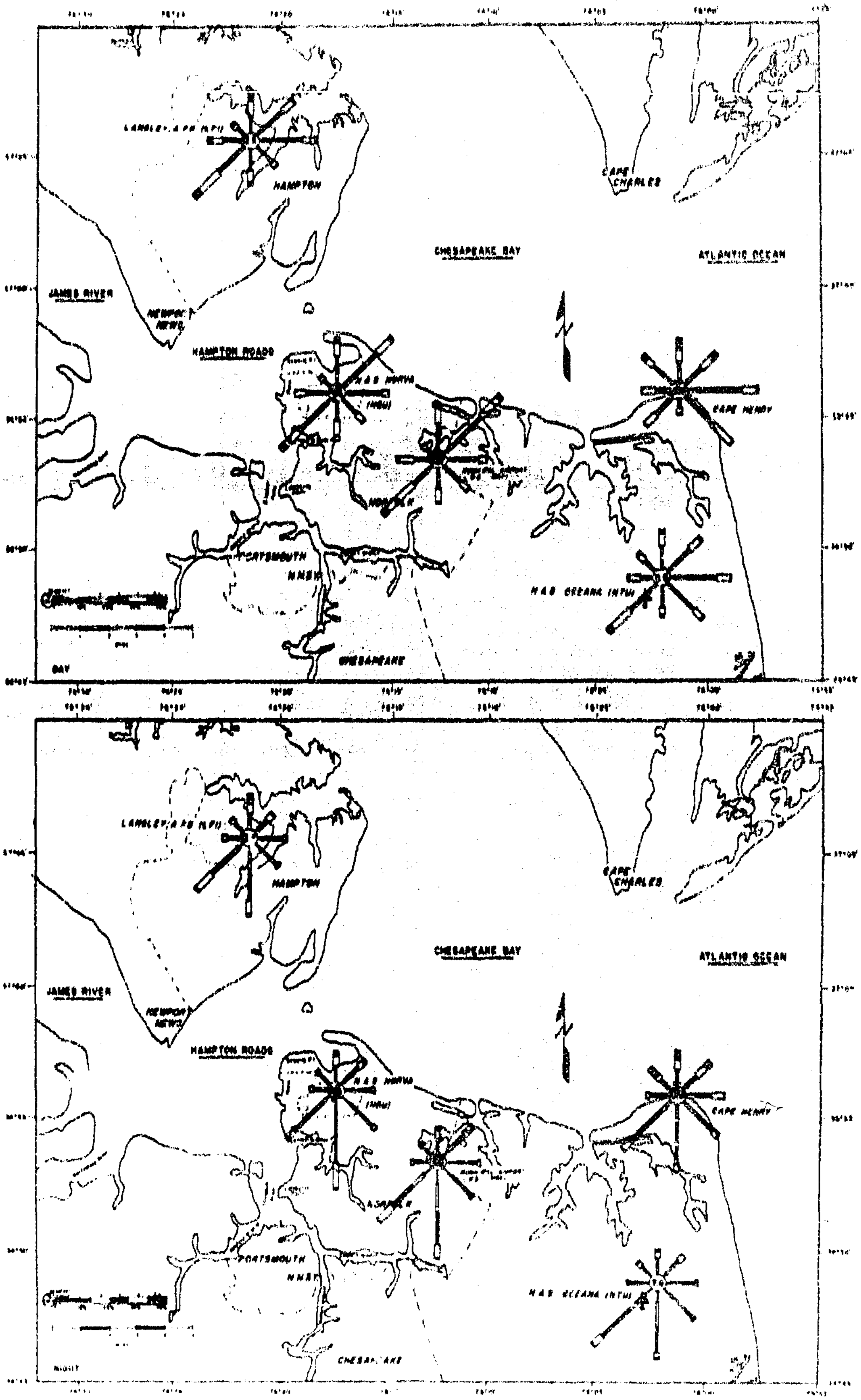

Figure 3.11. May Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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westerly winds are frequent at all stations, except Cape Henry, where the wind is southeast. Northwest winds are (again, with exception of Cape Henry) plainly infrequent. The sea breeze at the Air Station and Cape Henry shows up especially well at 1400 LST. A look at the May, night winds (fig. 3.11) indicates a diurnal change not only similar but of greater magnitude than that of April; as winds with northerly components become infrequent and south winds become predominant. In particular the east or northeast frequencies, associated with sea breezes and evident during the day, are considerably diminished. The nightly predominance of south winds in spring shifts somewhat to the southwest during May. The prevalence of south or southwest winds, at this time of year, if attributable to a land breeze circulation, should show a maximum around the time of maximum landmass cooling; a comparison of 0400 LST and all night wind roses bears this fact out. Day wind velocities decrease from April to May and the nights begin to show an increased frequency of calms.

(c) Summer (June, July, August)

The effect of the *Bermuda high* on the circulation in the Hampton Roads region in summer can be seen in figure 3.12, frequent southwest winds are in evidence at all stations. Northwest winds, since primarily an aftermath of cold fronts, are rare, and when they occur are considerably weaker than their spring or winter counterparts. A sea breeze is well in existence and is especially evident at Norfolk Municipal Airport. The breeze, however, does not extend too deeply inland as it is seldom felt in Portsmouth, which is located about 10 miles from the bay. Diurnal changes, as can be seen in figure 3.12, are greatest in summer. A nightly gentle south through southwest *prevailing wind* is plainly evident at all stations, and is due to the coupling of the circulation around the *Bermuda high* and the night land breeze. Other wind directions during the summer are infrequent. Both day calms and night calms are frequent in summer; wind speeds average 9 knots during the day and 6 to 7 knots at night.

Figures 3.13 through 3.15 represent the day and night wind roses for the individual summer months. These will be discussed together as it is evident that little difference exists between individual months in themselves, and between the individual months and the average summer roses. The month of July deviates most (but not greatly) from the two other summer months. In July the *Bermuda high* is strongest and produces a higher frequency of day and night southwest winds than June or August. Sea breezes are also slightly reduced in July since the warming coastal waters, along with the closer location of the Gulf Stream, reduces the land-water, mid-day temperature contrasts. The frequency of northwest winds, although low in June and August, is even more reduced during July — the month of highest temperature. July has the lowest wind speeds both day and night of any month of the year. The June and August wind distributions are quite similar in both direction and speed and show some spring and fall influences, respectively.

(d) Fall (September, October, November)

Fall wind distributions (fig. 3.16), although showing considerable uniformity, reflect the increasing number of *low* and frontal passages as north through northeast winds become prevalent. This preference is not as pronounced at Cape Henry or Oceana which have more uniform distributions. Winds from a southwest direction, so frequent in summer, decrease noticeably in the fall. The autumn increase in northeast winds is a result of anticyclonic flow around the eastern side of *highs* located to the north of the region; afternoon sea breezes still occur in early fall and also contribute to the increased northeast frequency. Northwest and southeast winds for the Roads neighboring stations are least prevalent. Night winds in fall (fig. 3.16), in addition to showing some diurnal change in wind direction, become calm more frequently than in any other season. Langley AFB has calms 21.3 percent of the time and Oceana 14.1 percent. The diurnal and seasonal increase in calms at Norfolk Municipal Airport is not as pronounced as at the other stations; its maximum in nighttime calms occurs in the summer. The main diurnal wind direction changes are, as with other seasons, a decrease in northerly winds and an increase in south winds; these changes are, however, not as striking as in summertime. Deviations from normal wind patterns are apt to occur in the fall, as the probability of hurricanes affecting the area is at a maximum.

The September wind roses (fig. 3.17) indicate a predominance of north through east winds at all stations. The *Bermuda high* breaks down

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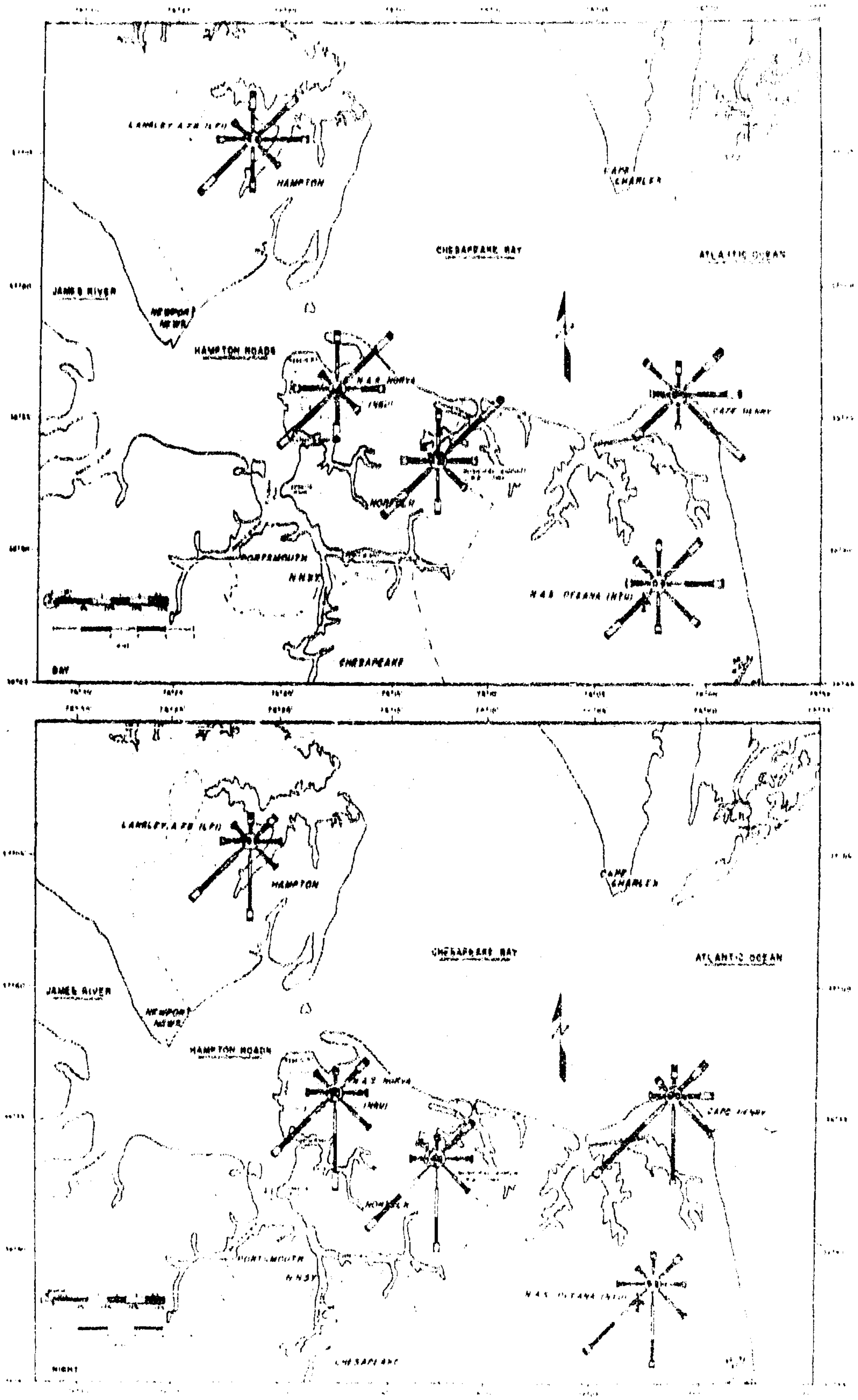

Figure 3.12. Summer Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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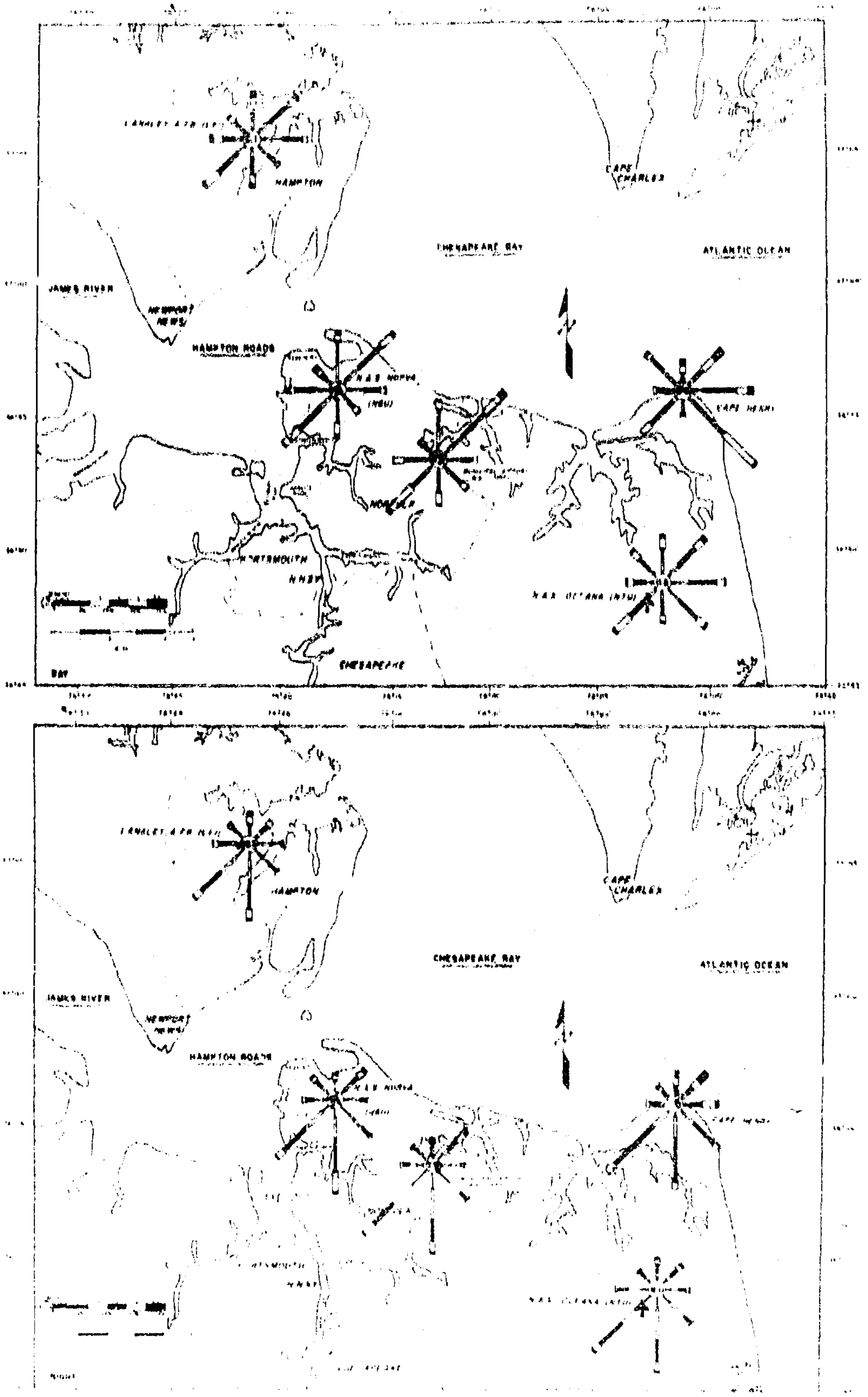

Figure 3.13. June Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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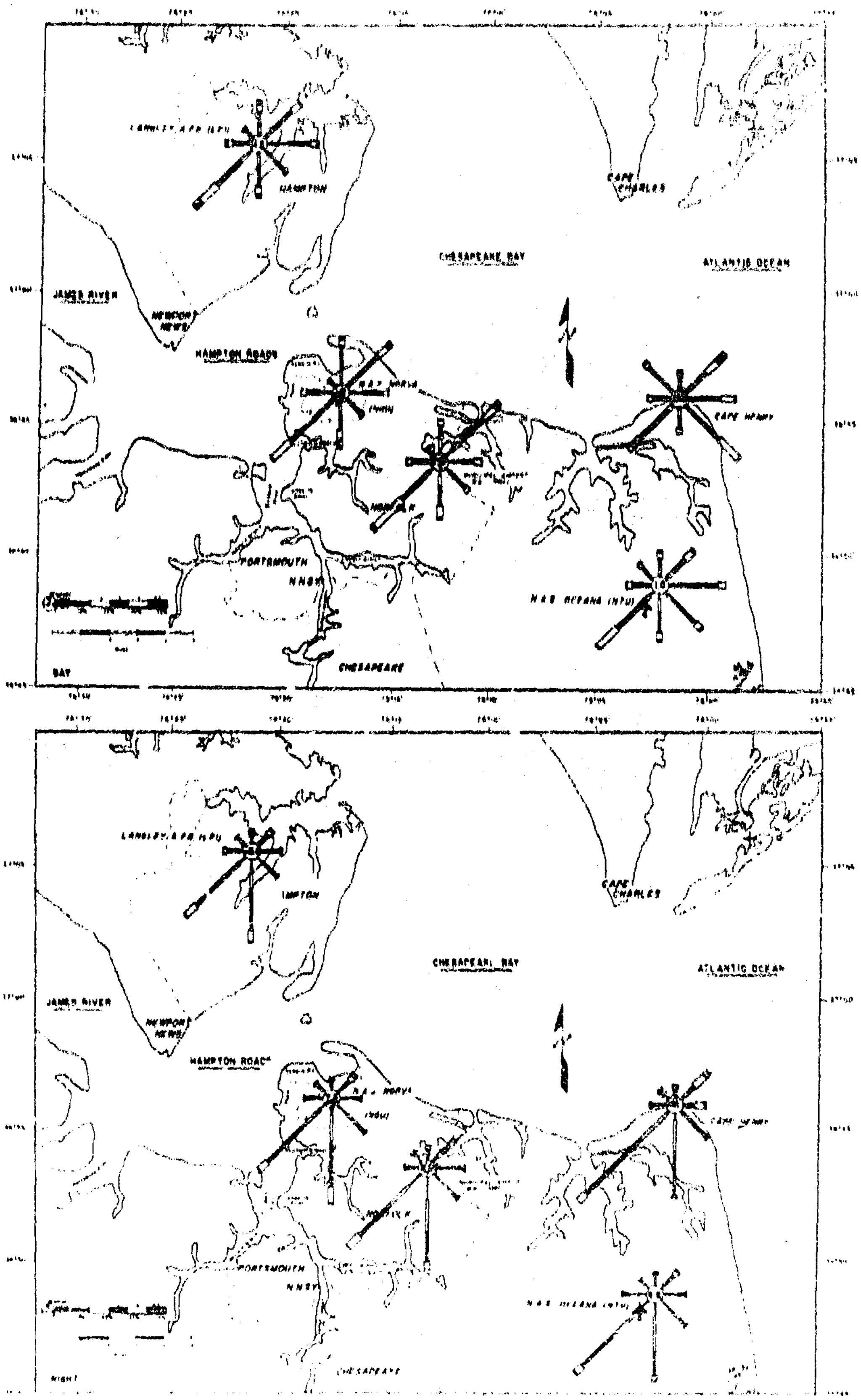

Figure 3.14. July Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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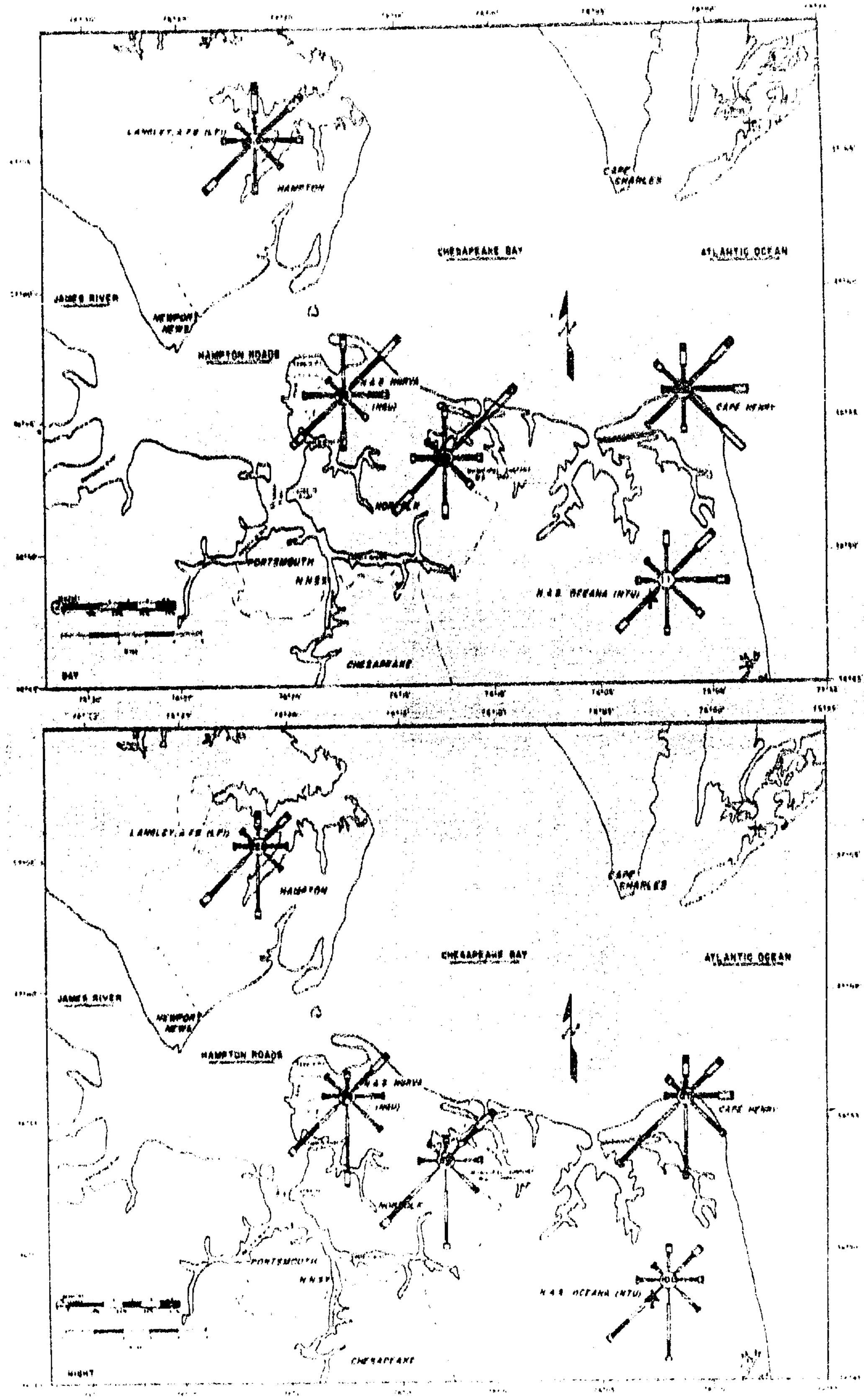

Figure 3.15. August Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations

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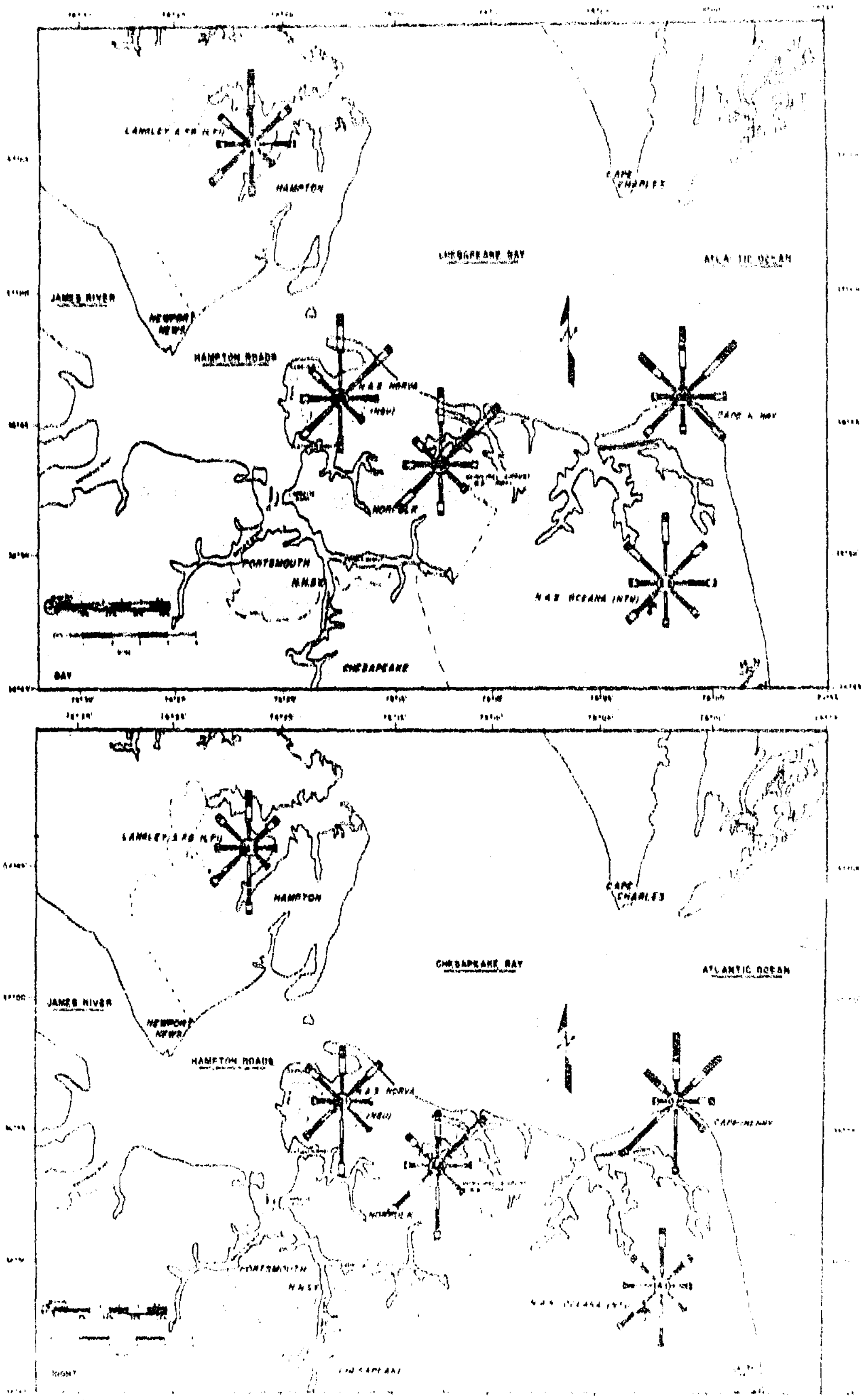

Figure 3.16. Fall Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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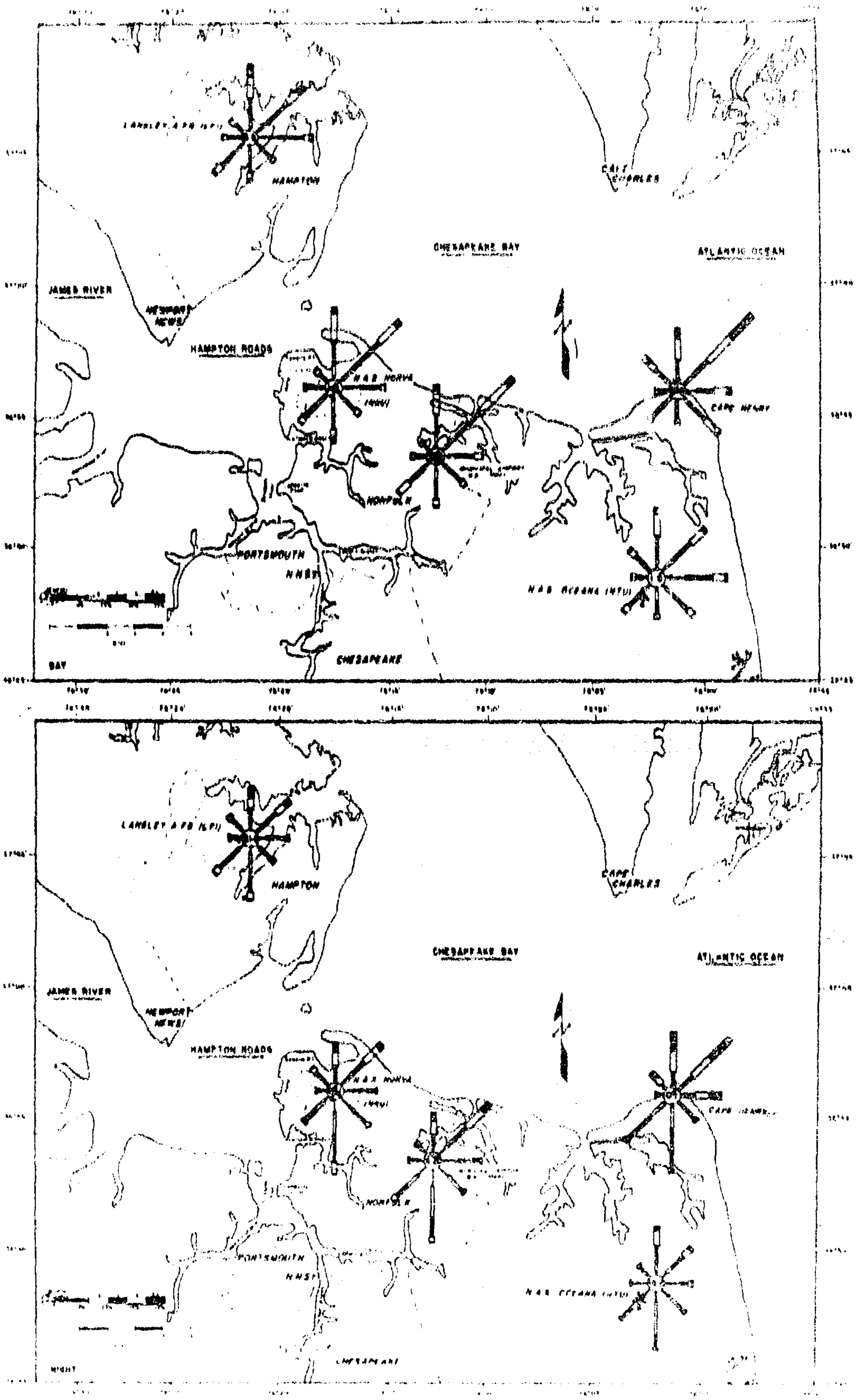

Figure 3.17. September Frequency (%) of Wind Speed Direction for Five Hampton Roads Stations.

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and the region experiences an increased frequency of frontal passages. The fronts in these latitudes become east-west orientated with anticyclonic flow behind them, and upon passage produce north through east winds rather than the normally thought of northwest winds. Also toward the latter half of the month, *Hatteras lows* contribute to the frequency of northeast winds. A sea breeze effect evidently reinforces the prevalent northeast wind in midafternoon, as a comparison of the 1400 LST wind rose and all, day wind roses shows a more frequent northeast wind at this hour. September diurnal changes (fig. 3.17) consist more of wind speed changes than of wind direction. The more pronounced subsidence inversion, found on the eastern side of the high pressure cell which follows frontal passages, caps off the surface from the upper flow and produces more calm winds than are found in summer when this area is under the western side of a high pressure cell. The diurnal wind direction changes, which are in evidence, are mainly those previously encountered; increase in south winds and decrease in north winds. Although September shows a high frequency of calms, the average wind speeds are higher than those of August.

October wind roses (fig. 3.18) show a similarity to September, except that east winds are less frequent and northwest winds more frequent. The area is more affected by offshore *lows*, producing north through northeast flow, than by easterly post, cold frontal anticyclonic flow present in early September; the increased frequency of cold air outbreaks is responsible for the increase in northwest winds. Westerly and southwesterly winds are, in the vicinity of the Roads, least prevailing. The October nighttime winds shown in figure 3.18 represent diurnal changes similar to those discussed for September. Wind speeds in October are somewhat higher than September and average 9 to 10 knots at day and 7 to 8 knots at night. Cape Henry exhibits no diurnal change in wind speed in October.

The November wind roses for daytime conditions (fig. 3.19) reflect the increased frequency of strong cold front passages and show considerable uniformity in the south clockwise through north directions for Langley and the two Norfolk stations. Oceana and Cape Henry show less uniformity in this semicircle, as southwest and northwest through north winds predominate. Easterly winds at all stations are in the minority. Like October and September, the November diurnal changes are small and consist more of a velocity decrease than any marked directional changes; although the increased frequency of south winds, as was evidenced for other months, is also present. November wind speeds show little deviation from September and October averages.

(e) Aloft

Wind roses for heights of 150, 300, and 500 meters were constructed to check on the variation of wind with height, since speed and direction remained essentially unchanged, these roses were not included in the publication.

3.3.2 Inversions

An important factor inhibiting the rapid dispersion (in both time and space) of an atmospheric pollutant is the presence of an inversion, either surface based or based at some higher altitude. Table 3.1 presents the percentage frequencies of low-level inversions at Norfolk Municipal Airport by seasons and by wind speeds of (a) 10 knots and less, and (b) greater than 10 knots. These inversions were determined from 0000 GMT (1900 LST) and 1200 GMT (0700 LST) soundings[1] and as such represent nocturnal radiation inversions more so than daytime inversions; inversions during the daylight hours are infrequent compared to night hours and, when they occur, are usually due to larger scale weather systems. On an annual basis nocturnal low-level inversions are present 57.0 percent of the time. Surface based inversions are by far more frequent than inversions based between the surface and 1,500 feet; also, surface inversions with surface wind speeds of 10 knots or less occur much more often than when surface winds are greater than 10 knots. The 10 knot point for the inversion classification by speed was suggested by the raw data; the inversion frequencies for individual wind speeds below 10 knots were distributed such as to make any further breakdown meaningless. No inversion classification by set wind speeds could be noted for inversions above the surface and at or below 1,500 feet; however, for presentation purposes, the same wind speed classification as for surface inversions was used.

Winter with its long nights is the season with the highest frequency of nocturnal low-

[1] *The data years for the inversion study are 1 January 1957 through 31 December 1961; due to the changeover from radiosonde synoptic times of 0300 GMT and 1500 GMT to 0000 GMT and 1200 GMT on 10 June 1957, the first 6 months of the data included only 0300 GMT soundings.*

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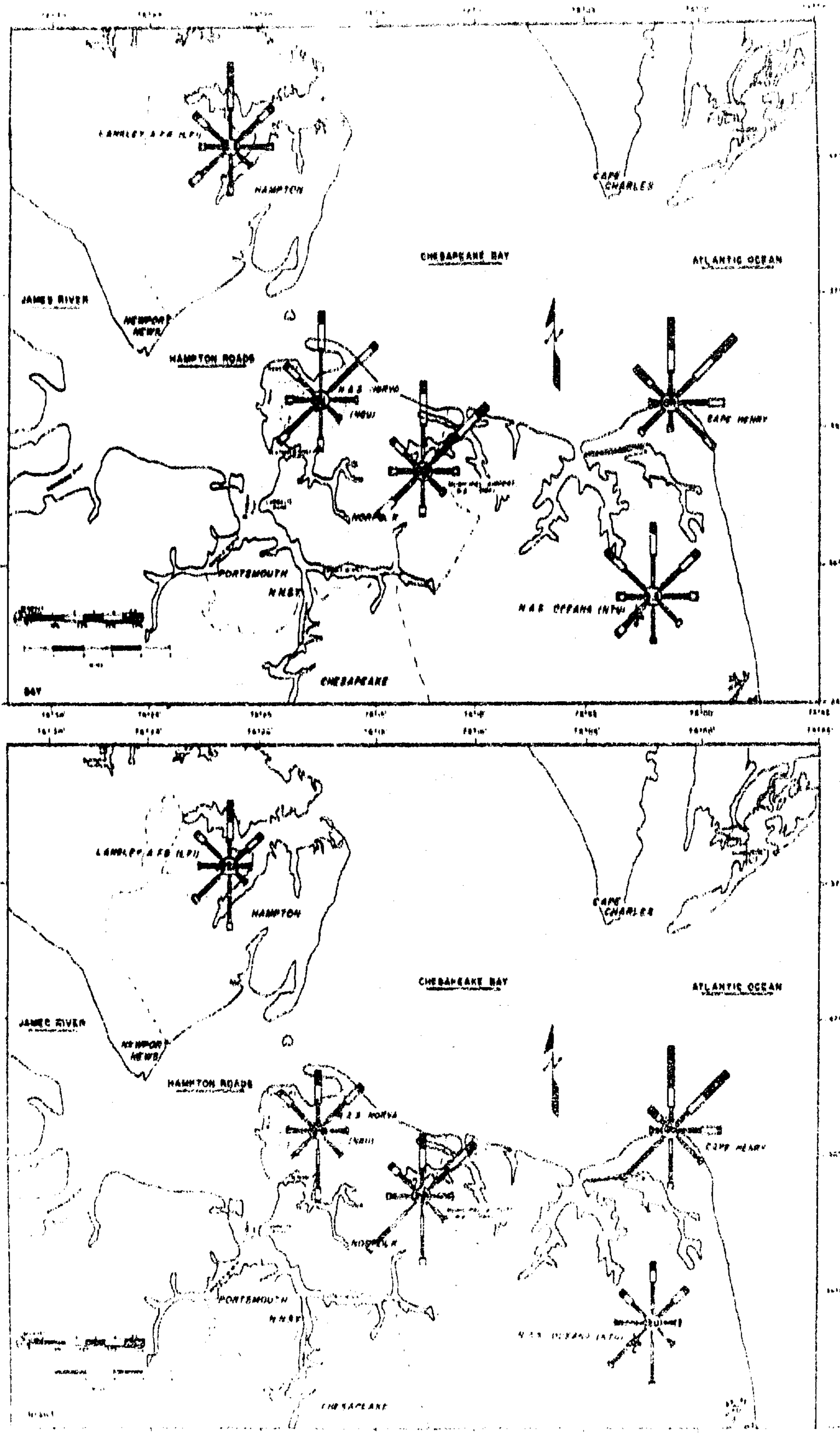

Figure 5.15. October Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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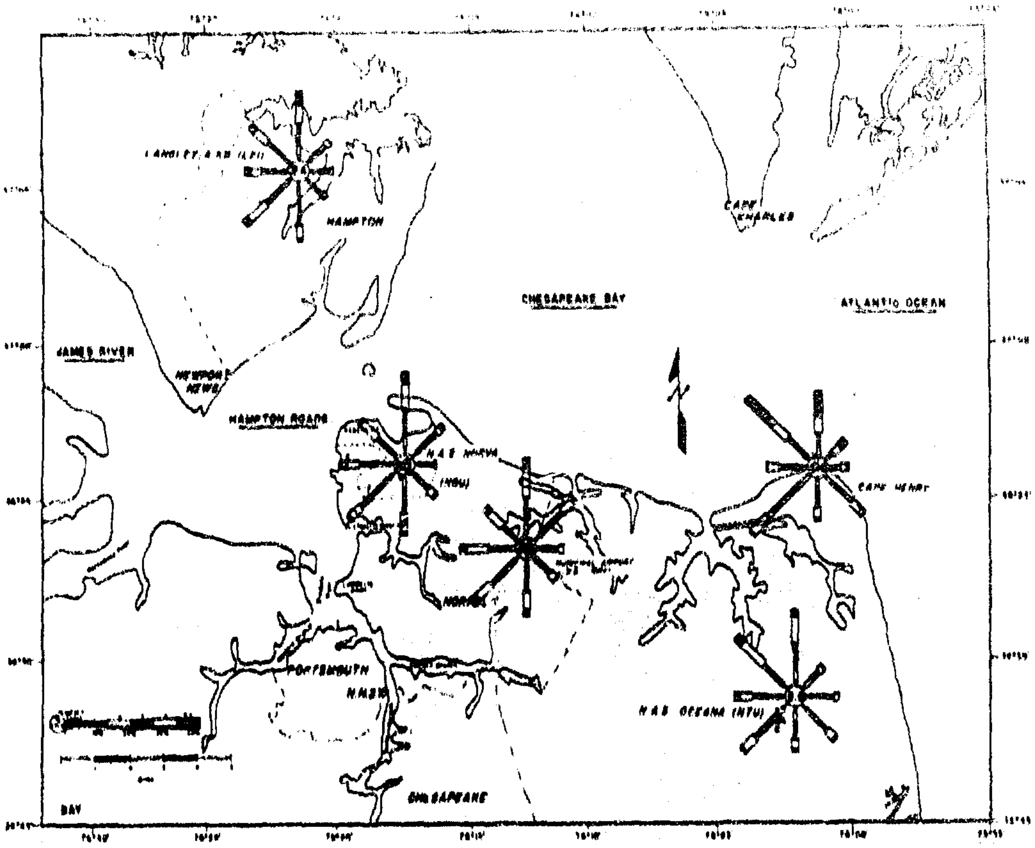

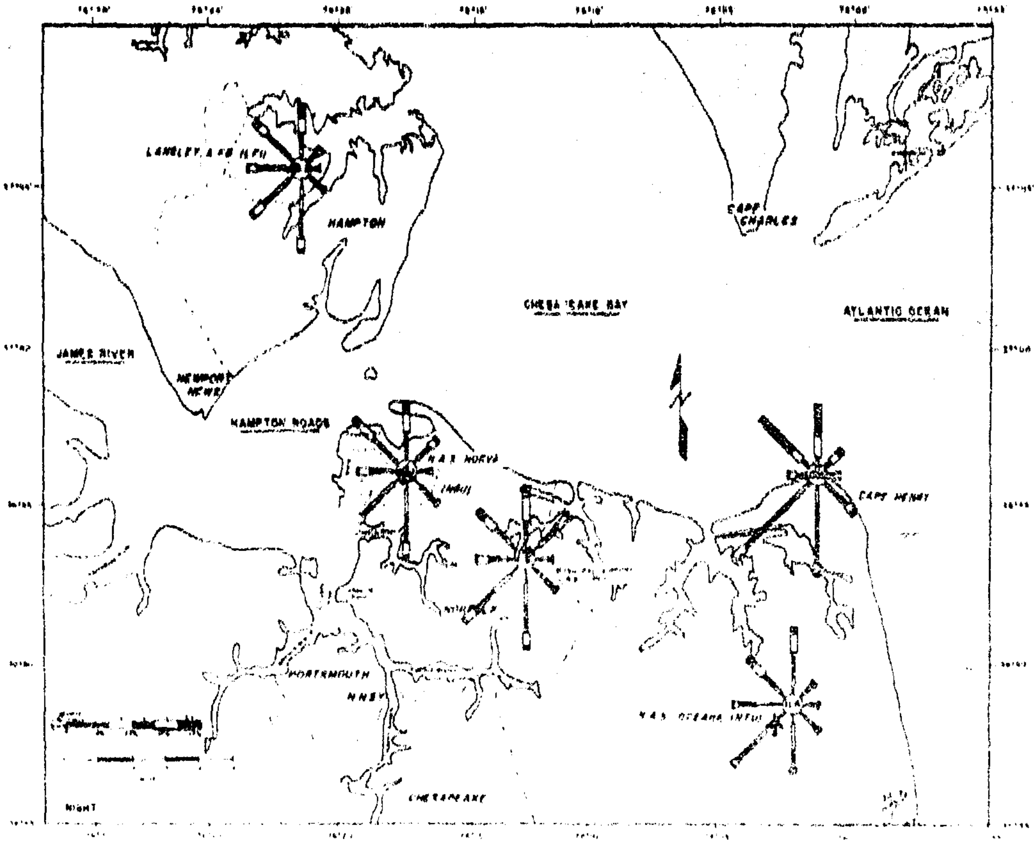

Figure 3.19 November Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations.

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Table 3.1. Annual and Seasonal Frequency of Low-Level Inversions.

SEASON	INVERSION HEIGHT						TOTAL
	Surface			>Surface ≤1,500 feet			
	Surface Wind Speed ≤10 kt.	Surface Wind Speed >10 kt.	Surface Wind Speed Total	Surface Wind Speed ≤10 kt.	Surface Wind Speed >10 kt.	Surface Wind Speed Total	
Winter	46.6%	8.9%	55.5%	9.3%	6.1%	15.4%	70.9%
Spring	30.4%	6.4%	36.8%	10.3%	7.0%	17.3%	54.1%
Summer	29.6%	2.5%	32.1%	10.7%	5.1%	15.8%	47.9%
Autumn	45.3%	3.7%	49.0%	4.5%	2.6%	7.1%	56.1%
Annual	38.0%	5.3%	43.3%	8.6%	5.1%	13.7%	57.0%

level inversions, 70.9 percent of the time; and summer, the season of minimum frequency, has 47.9 percent. Autumn and spring both have approximately the same number of inversions.

(a) Surface Based

If one first considers surface inversions, then winter still has the maximum (55.5%); however, autumn (with its clear, calm nights) is close behind (49.0%); spring and summer now are the seasons of minimum inversions. The above similarity in frequency of inversions for winter and autumn (fall) on one hand, and spring and summer on the other is more evident if one considers only surface inversions with surface wind speeds of 10 knots or less; in this case fall (45.3%) and winter (46.6%), and spring (30.4%) and summer (29.6%) are essentially identical. The frequency of surface inversions with surface wind speeds greater than 10 knots is low, 5.3 percent annually with a range from 8.9 percent in winter to 2.5 percent in summer. With these higher wind speeds the season of maximum surface inversion frequencies shifts from fall-winter to winter-spring.

Figure 3.20 presents an annual and the seasonal wind direction distributions associated with surface based inversions, using the same speed breakdown as was used for the percentage frequency tabulation. Clearly evident during inversions, with low wind speeds (≤ 10 knots), are the preferred southwest and south wind directions during all seasons of the year, and especially in summer and spring. Inversions with winds from a west through northwest direction are relatively infrequent; winds from this direction, quite often a result of a cold front passage, have a relatively higher velocity and the accompanying air mass is usually unstable in the lower layers (cold air over a warmer surface). Wind roses for inversions with surface wind speeds greater than 10 knots indicate, even more pronouncedly, the preferred southwest and south wind directions during inversions; in addition, a secondary maximum, a north wind, in fall and winter is also in evidence for those higher wind speeds.

(b) Above Surface, but At or Below 1,500 Feet

The seasonal variation for inversions above the surface and at or below 1,500 feet is small. Spring has the highest total frequency (17.3%) with summer (15.8%) and winter (15.4%) frequencies being somewhat lower; autumn frequencies (7.1%) represent about one-half of the frequencies of the other seasons. The speed breakdown for these inversions does not yield any further information than is apparent in the total frequencies. The relatively higher percentages of these inversions found in spring and summer is due to surface heating which has taken place by the time of the 0700 LST (1200 GMT) sounding. This heating causes the lifting of a surface based inversion.

The wind roses presented in figure 3.21

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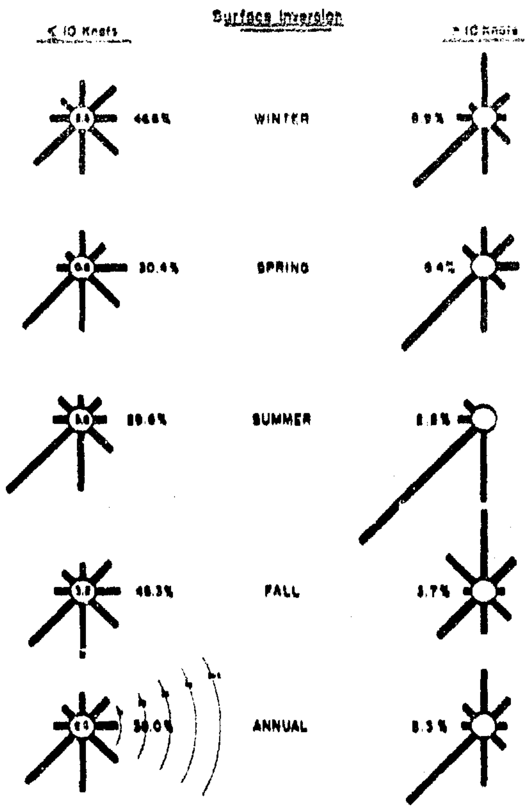

Figure 3.20. Annual and Seasonal Wind Directions During Surface based Inversions at Norfolk (ORF). Wind Speeds: ≤10 knots, and >10 knots.

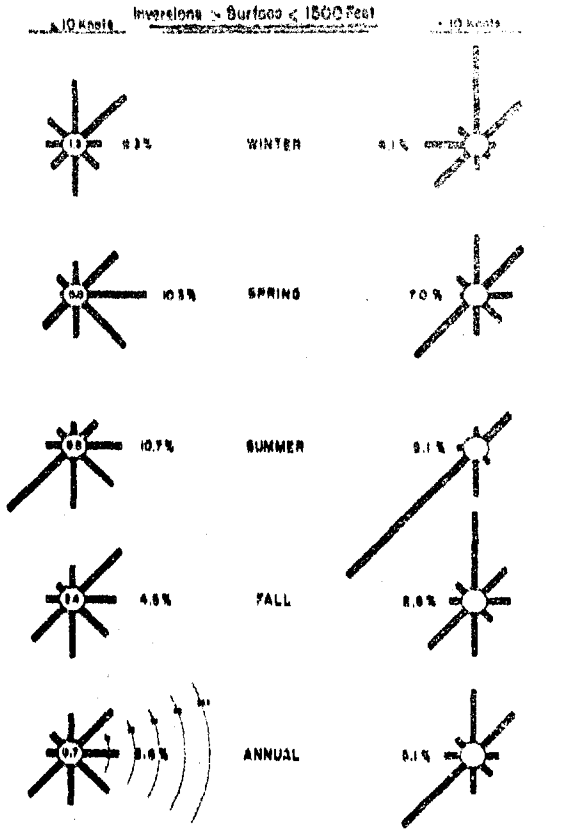

Figure 3.21. Annual and Seasonal Wind Directions During Inversions between the Surface and 1,500 feet at Norfolk (ORF), Wind Speeds: ≤10 knots and >10 knots.

show considerable difference from the surface inversion roses when compared seasonally. The main difference being an increase in inversions with northeast and east winds and a decrease in inversions with southwest winds; winter shows the greatest difference in the two inversion classifications and summer shows the least. However, the annual comparison of wind roses for these two classes of inversions shows considerable similarity; the basic differences evident in the seasonal comparison, although still present, are smoothed.

3.3.3 Elements of Weather

(a) Precipitation

Precipitation is related to pollution in that rain (or snow) may act as a ''cleansing'' agent in the atmosphere and suppress the wide-spread dispersion of a pollutant, producing heavier dosage and deposition nearer to the source.

The Hampton Roads region, being influenced by middle latitude cyclones in the colder season and thunderstorms during the warmer months, does not have a characteristic dry season. Figure 3.22 portrays, by months, the mean number of days with .01 inches or more of precipitation; the range is narrow and is from a maximum of 12 days in March (also 11 days in April and July) to a minimum of 8 days occurring on four separate months — June, September, October, and December. The driest successive months are October through December and the wettest successive months are March-April and July-August.

Referring back to figure 3.2, one can see a somewhat different presentation of precipitation data, here normal total monthly precipitation is portrayed. July has the highest total monthly rainfall, nearly twice that of March. Thus, although March has more rainy days than July, the amount of rain (over .01 inches) falling

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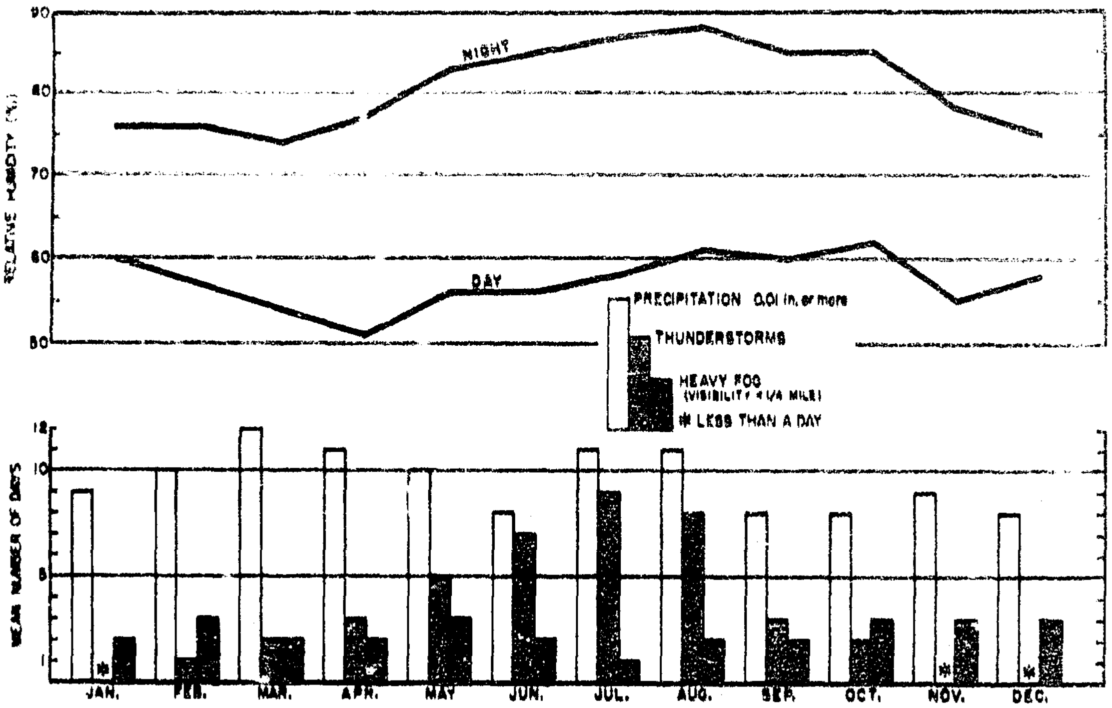

Figure 3.22. Annual Variation at Norfolk (ORF) of: (a) Number of Days Each Month With Precipitation, Thunderstorms, and Heavy Fog; (b) Average Monthly Relative Humidity (%) – Day and Night.

on a given March day is less than on a July day. Precipitation in March is more of the light, warm front type; whereas July has intense showery precipitation associated with thunderstorms. The fall months, considering both forms of precipitation presentation (figs. 3.2 and 3.22) show both fewer rainy days and a smaller total amount of precipitation. Annual snowfall amounts are small, 4.7 inches on the average; only two days per year have more than 1 inch snowfalls.

Figures 3.23 through 3.27 indicates annual and seasonal wind direction and speed during day precipitation and night precipitation; these roses present much m[illegible] uniformity between stations than the nonprecipitation roses previously presented. The annual day roses (fig. 3.23) portray the influence of the most common rain producer in the area — an offshore, northeasterly-moving, low pressure system which produces north or northeast winds and usually rain. The remaining wind directions, on an annual basis, are approximately equal as rain producers; however, at all stations west winds and calms are the least common during day precipitation. Annual night roses (fig. 3.23) do not indicate any significant diurnal changes, either in wind speed or direction, during precipitation.

The winter day roses (fig. 3.24) depict the influence of precipitation-producing cold frontal passages, which produce northwest through north winds in this region; influences of offshore *lows* are also evident but in not as pronounced a fashion as on an annual basis. Diurnal changes (fig. 3.24), in evidence in the nonprecipitation roses, are essentially absent due to the presence of clouds (which suppress outgoing radiation) and to stronger pressure gradients during precipitation.

Winds during precipitation in spring (fig. 3.25) are mainly from the north through east. A significant decrease is noticeable from winter to spring in northwest winds. Winds from the south clockwise through northwest are least predominant. Springtime rain is associated with winds having an over water trajectory and, hence, with winds which have easterly compon-

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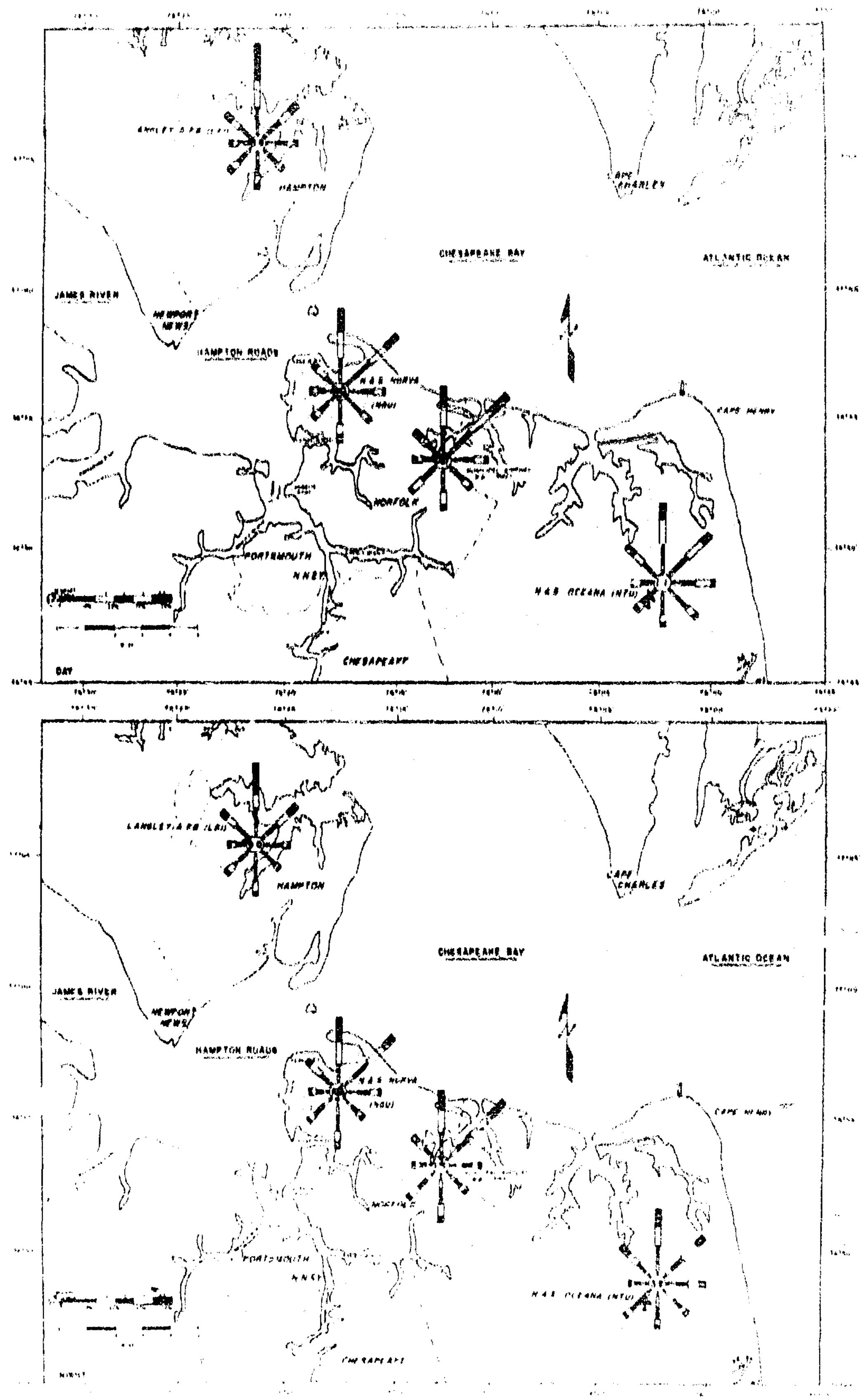

Figure 3.23. Annual Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations When Precipitation is Occurring.

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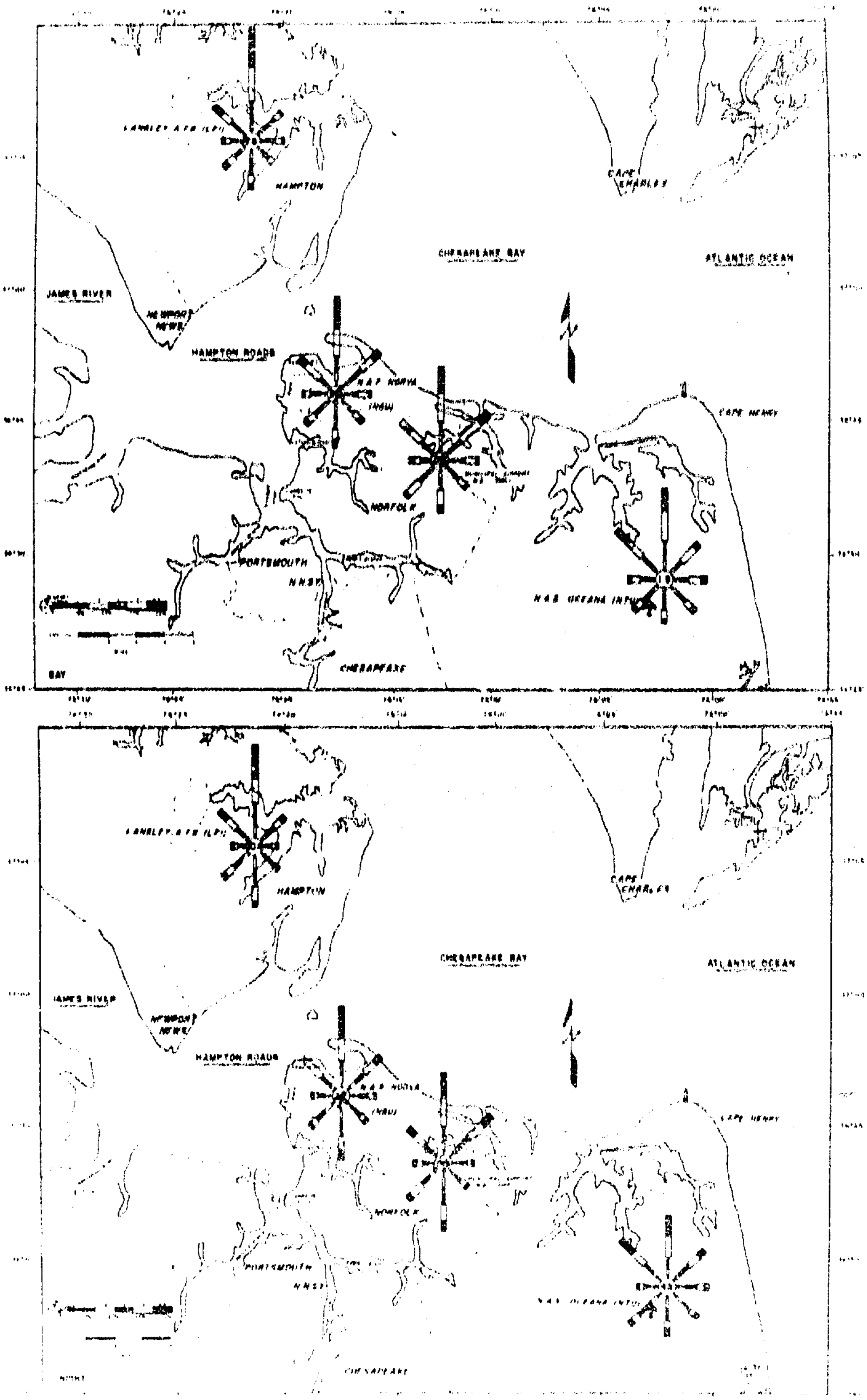

Figure 3.24 Winter Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations When Precipitation is Occurring.

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ents. The night winds (fig. 3.25), except for a slight decrease in speed, show little diurnal change during precipitation.

Summer, with some exception in winds from the west and northwest, shows the most uniform wind distribution of all seasons (fig. 3.26). More uniform wind roses would be expected in summer, since thunderstorms — the main contributor to summer precipitation totals — are apt to be randomly located with respect to a station, thus resulting in random wind directions during precipitation. The slightly higher northeast wind frequency is due, in part, to offshore *lows* which can occur in summer and which result in overcast days with light precipitation. The diurnal changes in summer precipitation wind roses, evident in figure 3.26, are mainly an increased frequency of southwest winds.

The north through northeast predominant wind directions for fall day, precipitation wind roses (fig. 3.29) indicate that offshore cyclonic developments are responsible for autumn precipitation in this region. The remaining wind directions are relatively infrequent and uniform among themselves. Fall, in addition to summer, also shows some diurnal change (fig. 3.27), as the frequency of northeast and northwest winds increase, and the frequency of north winds decrease slightly. The fall night winds show predominant northwest through northeast winds during precipitation; the remaining directions east through west are uncommon.

(b) Thunderstorms

From a pollution standpoint, thunderstorms are important not only because of the rainfall they produce but also because they serve as indicators of atmospheric stability; i. e., low-level. Months which indicate a high frequency of thunderstorms would also be expected to show strong (superadiabatic) lapse rates, which are more conducive to the vertical dispersion of a pollutant than neutral or inverted lapse rates; common during months of low thunderstorm frequency. For example, a July afternoon would disperse a pollutant more effectively than a November afternoon, on the average.

The monthly frequency of thunderstorms may be seen in figure 3.22, where the mean number of days with thunderstorms is given for each month. Thunderstorms are rare in January, begin occurring in February, gradually become more numerous with the approach of summer, peak in July-August, drop-off rapidly in September through October, and become uncommon in November and December. A *pure* air-mass thunderstorm is less common in this region (over land) than generally thought to be the case. Some convergence mechanism, in addition to solar insolation, is usually necessary for thunderstorm occurrence. The convergence mechanism may appear insignificant on a weather map, such as a slight cyclonic curvature of an isobar which is part of a high pressure cell, but a careful analysis of the synoptic situation will reveal that it is the spark which is needed to set off the activity. As a point of emphasis, thunderstorm can and do occur at night in this region.

(c) Fog

Fog, like thunderstorms, can be used to estimate atmospheric stability in the lower layers; the presence of fog, however, indicates rather stable conditions (as opposed to thunderstorms) and thus poor dispersion of a pollutant.

The mean number of days with thick fog (visibility less than 1/4 mile) per month is presented in figure 3.22. The monthly range of days is small with a minimum of 1 day in July and a maximum of 3 days occurring on 5 separate months. The fogs in the foggier successive months, October through December, are mainly due to radiation, a result of long nights and clear skies.

(d) Sky Cover and Clouds

The presence of clouds during the day inhibits solar heating at the surface, thus yielding poorer diffusion conditions. On the other hand, during the night, clouds tend to reduce outgoing radiation thereby reducing the possibility of an inversion formation and poor diffusion.

Monthly mean sky cover, from sunrise to sunset, is presented in figure 3.28a. The range is from a high of 0.65 in January to a low of 0.53 in November. Sky cover decreases from winter to spring, levels off in summer and fall, and begins increasing with the approach of winter. Another statistic of monthly sky condition is presented in figure 3.28b, where the mean monthly number of days with clear, partly cloudy, and cloudy skies can be seen. Cloudy (0.8 to 1.0 tenths sky cover) days are at a maximum in winter and early spring and are at a

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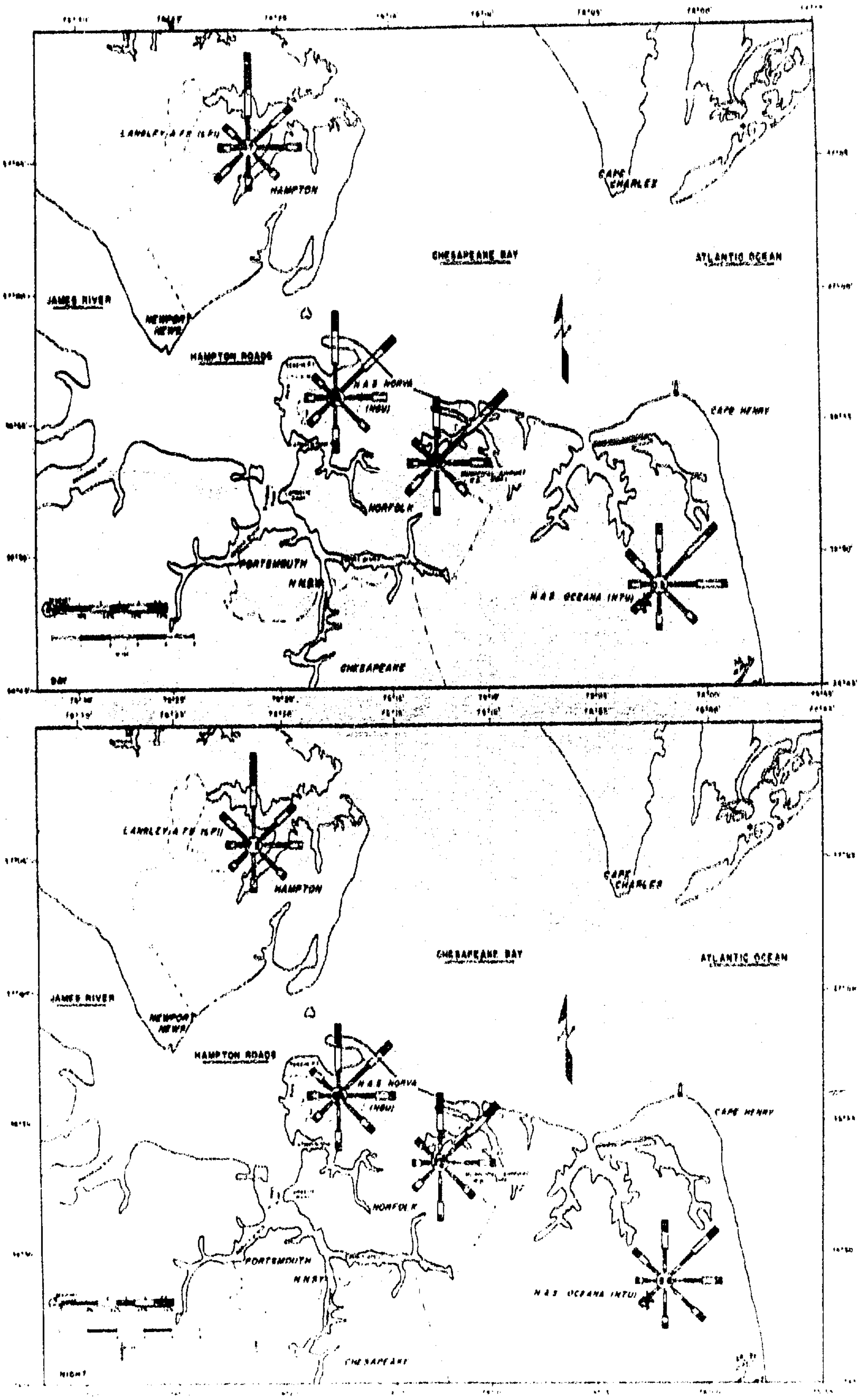

Figure 1.25. Spring Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations When Precipitation is Occurring.

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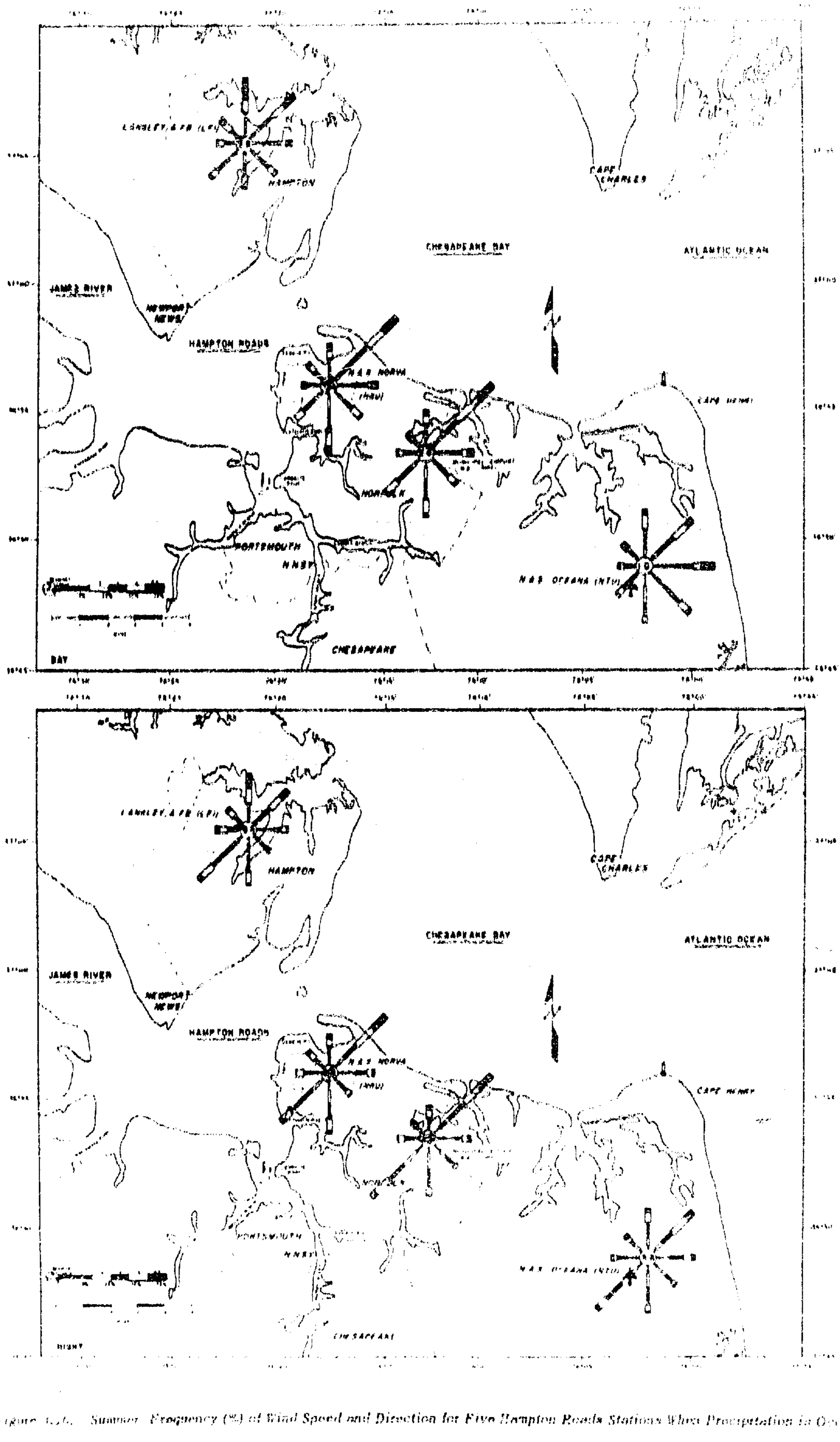

Figure [illegible]. Summer Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations When Precipitation is Occurring.

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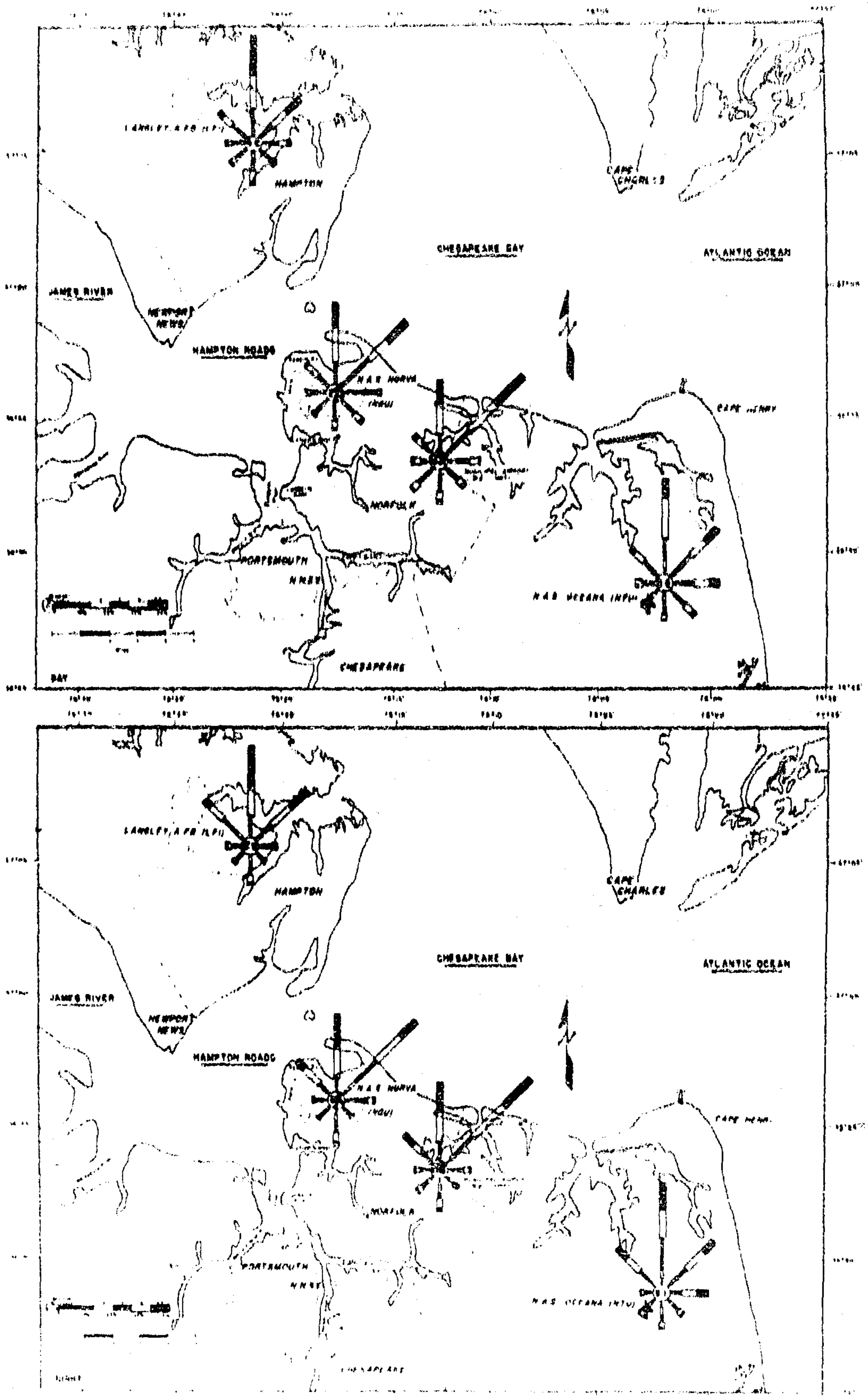

Figure [illegible] Fall Frequency (%) of Wind Speed and Direction for Five Hampton Roads Stations When Precipitation is Oc[illegible]

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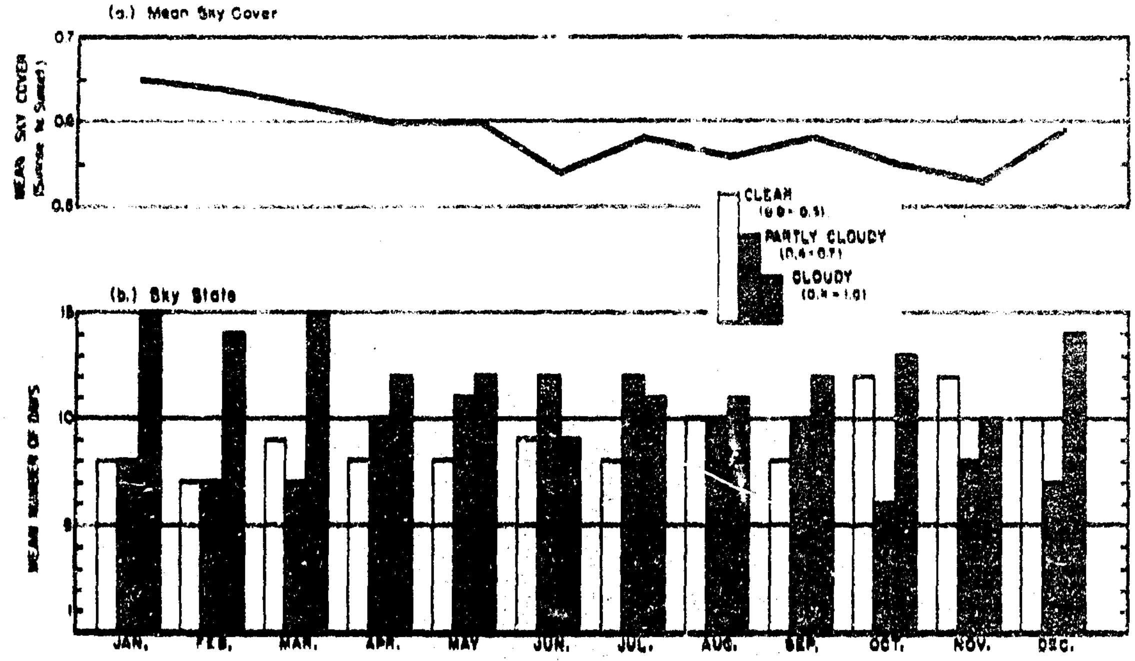

Figure 3.28. Annual Variation of Monthly Sky Conditions at Norfolk (ORF).

minimum in summer; June has the least number of cloudy days (9). Partly cloudy days (0.4 to 0.7) are more frequent in the warmer months as a result of convective activity which tends to be of a partly cloudy nature. The monthly range of clear (0.0 to 0.3) days is smaller than that of the other sky conditions, with October and November showing a distinct maximum. This maximum is due more to a reduction in days with partly cloudy skies than to a reduction in overcast days (convective activity decreases considerably in the fall).

One type of cloud, stratus, varies with considerable frequency and set of synoptic patterns in the area to warrant special discussion. Stratus (and sometimes fog) may be advected into the region from two different high pressure regions.

Northeast stratus is often found in spring and results from the typical synoptic situation presented in figure 3.29. The movement of a continental polar air mass or of a cold maritime polar air mass to a center over New England, with a wedge of high pressure extending along the Atlantic coast, causes easterly or northeasterly circulation in this region; the over water trajectory of this circulation, from relatively warmer Gulf Stream waters to the colder waters near the coast, is responsible for the stratus formation. This type of stratus is usually quite persistent and will sometimes last for days with only slight clearing during the afternoons of these days. The top of the stratus layer attains a height of 2,500 to 3,000 feet with bases averaging 50 to 800 feet. Wind speeds of 10 to 15 miles per hour are most favorable for these conditions.

The other type of common stratus is *south stratus*, most prevalent in summer; it is caused from an entirely different synoptic situation than the advective *northeast stratus*. *South stratus* (or fog) is usually caused by a combination of radiation and advection, and although occurring more often than *northeast stratus*, does not last as long; it usually forms between 0500 EST and 0600 EST and, due to strong summer heating, starts dissipating and lifting between 0800 EST and 0900 EST. *South stratus* (or fog), however, gives ceilings below 200 feet and visibilities below 1/2 mile about twice the number of hours as

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southeast stratus . Ideal summer *south stratus* conditions are caused by a moist maritime tropical air mass centered to the east or southeast of the region (fig. 3.30). This pattern is usually semistationary and once stratus or fog develops, it will occur on successive mornings as long as the circulation remains the same. Winds up to 10 to 12 miles per hour are likely to give a low stratus of fog condition, while winds of 12 to 16 miles per hour and over will result in stratus at 400 to 800 feet. Stratus decks are often thin on the first morning of their appearance, becoming more intense on successive mornings.

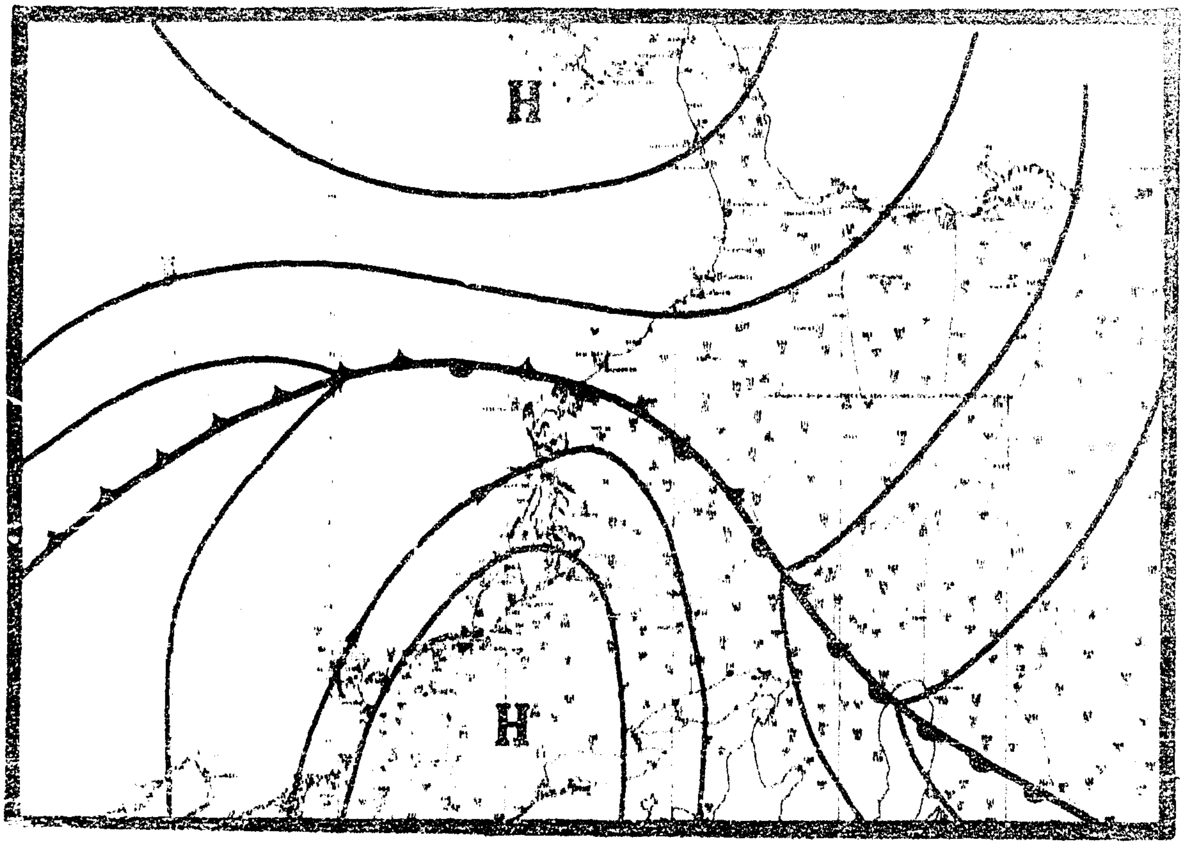

Figure 3.29. Stratus with an Easterly to Northeasterly Circulation.

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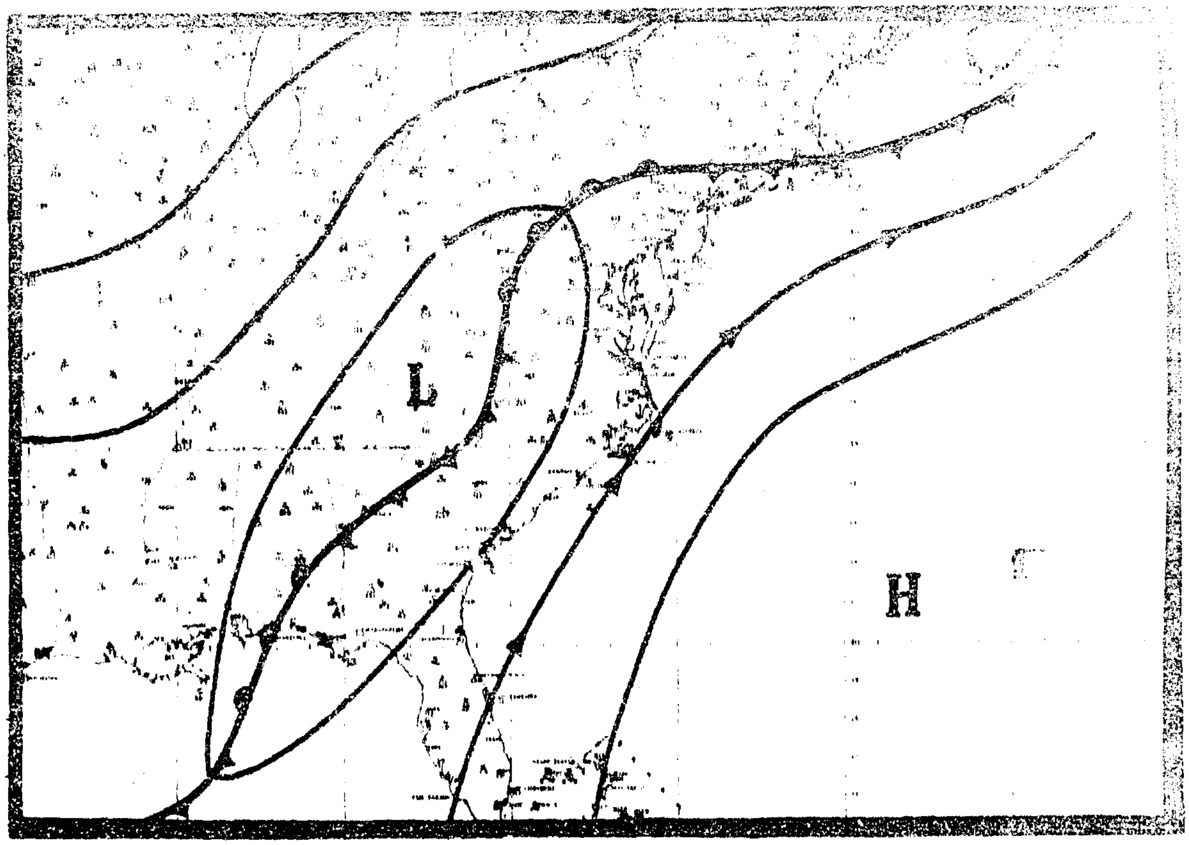

Figure 3.30. Stratus with a South to Southwest Circulation.

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4. THE POLLUTION POTENTIAL OF HAMPTON ROADS

In the foregoing sections, the major factors affecting the dispersion and deposition of contamination products and the climatology of the Hampton Roads area have been discussed as individual subjects. The fact that a major release itself is *most improbable* should be strongly stressed, but it is also interesting to review the probabilities of the various meteorological occurrences in the event of a pollutant release. This is a matter of combining the climatology, a map of the area, and the various diffusion patterns.

From the foregoing section, it should be evident to the reader that the *Hampton Roads area has a low pollution potential.*

4.1 Under Southwest Flow

The effect of the Bermuda *high*, with its southwest flow, is partly responsible for this low potential. Its effect is felt throughout the warm season and in many cases even in winter. Figure 4.1 might be considered as a probable day diffusion pattern during the warm season when the Hampton Roads area is under southwest flow (which is often); a mid-day wind speed of 8 knots (4m./sec.) and moderate insolation have been used for illustration. Assuming a release occurring in the center of the Roads, it can be seen that the significant dosages do not occur over any population centers and are restricted to water areas. Figure 4.2 is for a night release during southwest flow. This situation occurs even more often than day southwest flow, as it occurs not only in conjunction with the Bermuda *high* but also as a result of a local circulation set up under inversions during other times of the year; in fact, it is the most frequent wind direction during inversions (which occur more than 50% of the time). A speed of 4 knots (2 m./sec.) and a condition of less than 3/8 cloudiness has been assumed. Here, some significant dosages might temporarily effect the sparsely populated lower tip of the Delmarva peninsula as the plume made its way to the open ocean. However, in most cases meteorological conditions, with the onset of daytime, would change to some sort of lapse condition before significant dosages reached the peninsula.

4.2 Under Northeast Flow

The other wind direction which occurs frequently is a northeast wind. This can occur as a result of a sea breeze which is produced under weak gradient conditions in the warm season, or in other seasons as a result of offshore passing *lows* or the flow around the eastern edge of a high pressure cell. Figure 4.3 depicts the sea breeze situation; strong insolation and a wind speed of 4 knots (2m./sec.) are assumed. Here, also due to the large vertical diffusion coefficients involved, significant dosages do not reach land and occur over the water. The other conditions yielding northeast winds involve strong winds and cloudy conditions; figure 4.4 thus depicts both day and night diffusion (a wind speed of 20 knots is assumed and neutral stability). Although significant dosages extend over land areas (10 and 90 unit isopleths), lethal dosages (greater than 400 units) do not; also, it should be noted that the land areas over which these dosages occur are relatively sparsely populated.

4.3 Other Wind Flows and Conditions

A wind direction from the northwest would tend to disperse a pollutant over the metropolitan Norfolk area; however, as has been seen, northwest winds, contrary to expectations, are *infrequent* in the region. (Since winter storm tracks usually are far enough north of this region so that, following a cold front passage, this locale is under the anticyclonic flow of a cold *high* rather than the tight cyclonic circulation of a *low* , as is the case in New England.)

The cities of Hampton and Newport News also have a low pollution potential since a southeast wind, which is needed to carry a pollutant released in the Roads in their direction, is *rare* .

The study of the climatology has also shown that it is more probable that there will be *no* rain, fog, or thunderstorms (that is, the Hampton Roads region is not *extremely* wet or foggy, nor does it have *very numerous* thunderstorms), so that in an estimate of the *general* pollution potential of the area, it can be assumed that these meteorological events would not be taking place the majority of the time. It should be emphasized, however, that the deviations in diffusion values and marked deposition *could result* , in the event rain or showery precipitation associated with thunderstorms were occurring during a pollution episode.

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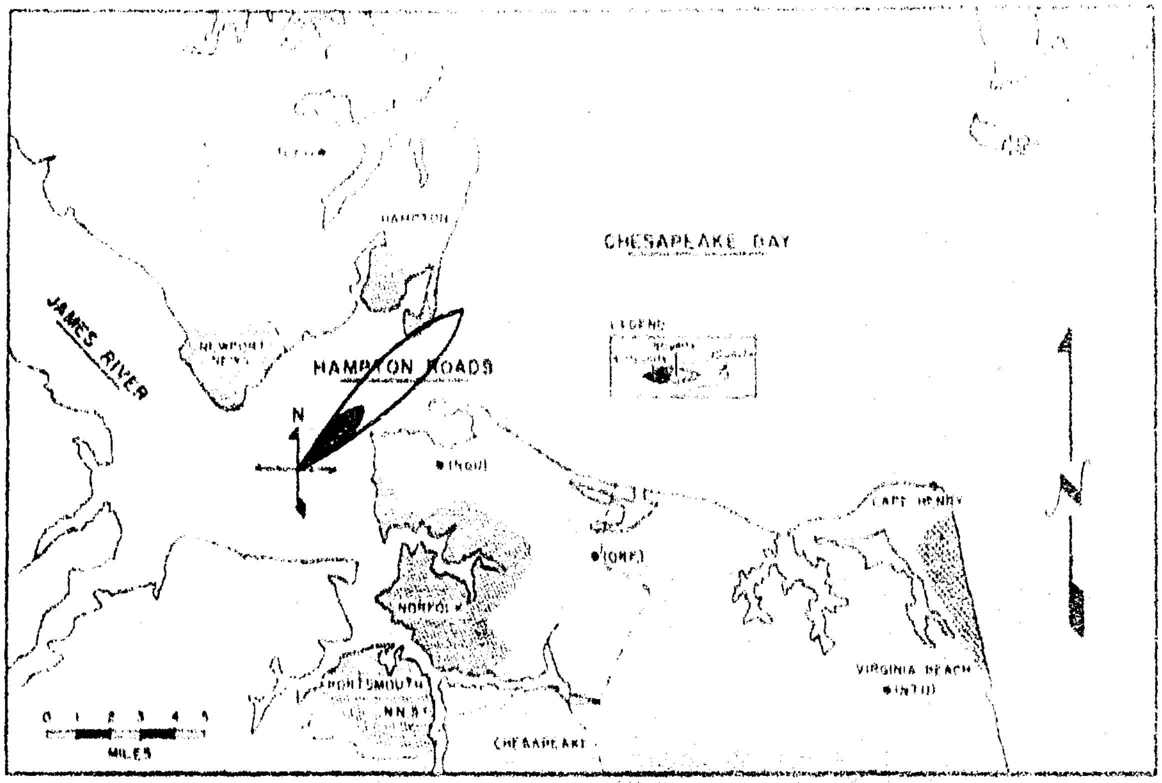

Figure 4.1. Probable Extent of Ground-Level Contaminant During a Typical Summer Day at Hampton Roads.

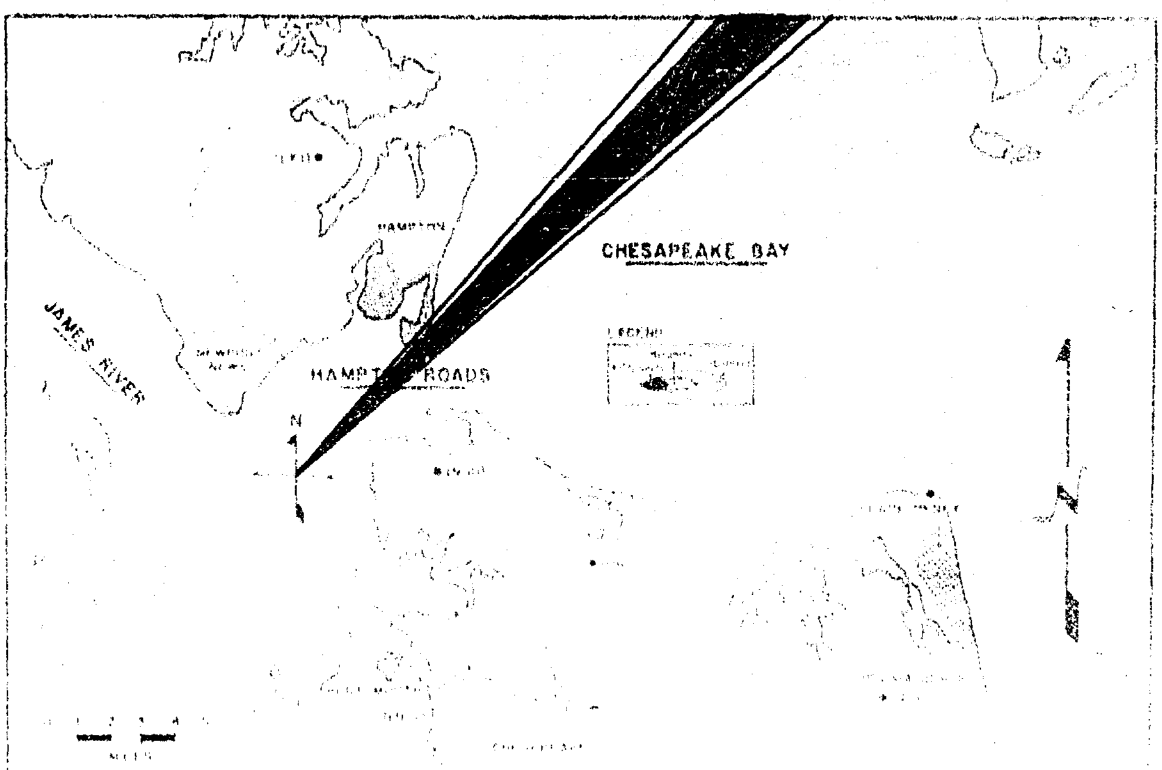

Figure 4.2. Probable Extent of Ground-Level Contaminant During a Typical Night at Hampton Roads.

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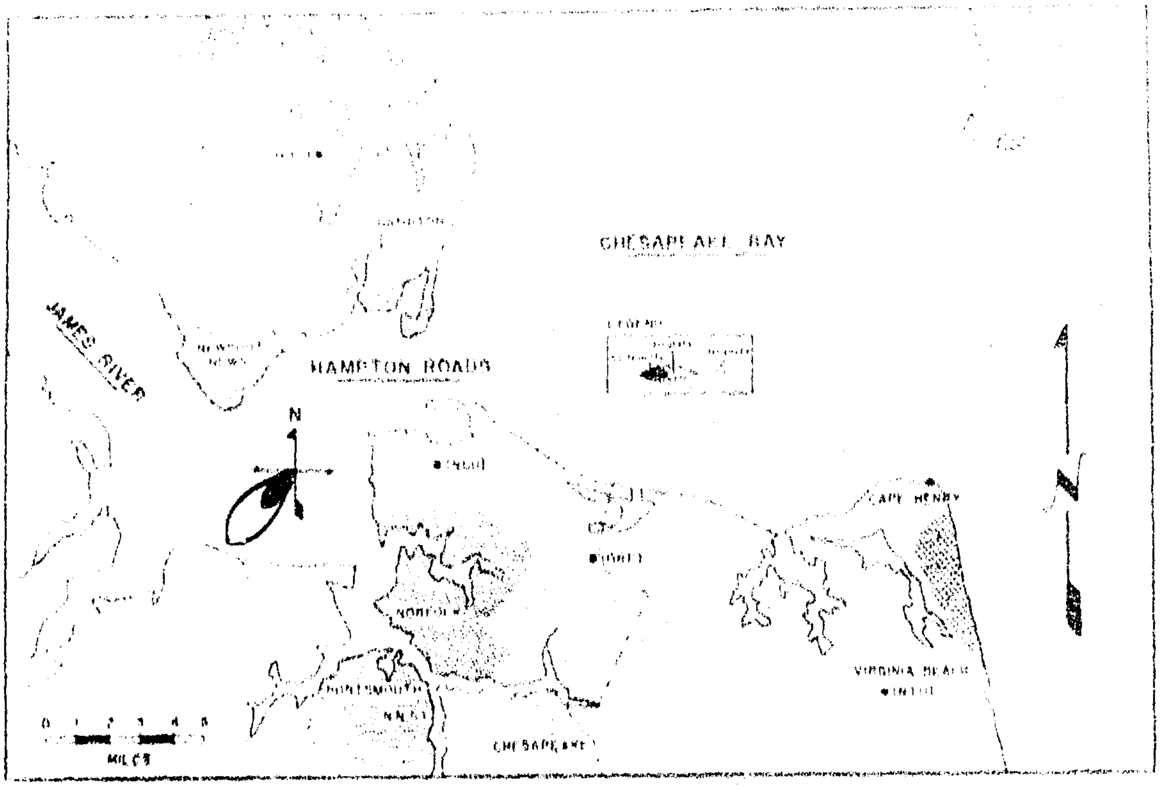

Figure 4.3. Probable Extent of Ground-Level Contaminant with an Afternoon Sea Breeze in the Hampton Roads.

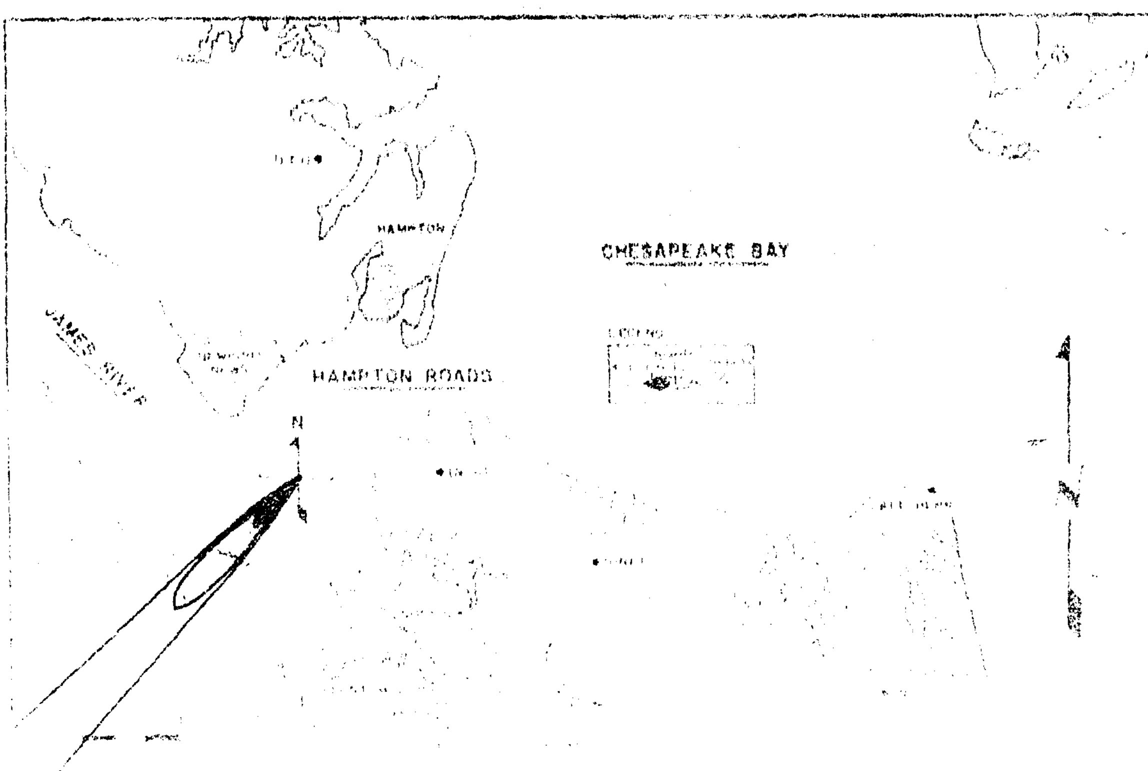

Figure 4.4. Probable Extent of Ground-Level Contaminant with Strong Northeast Flow in the Hampton Roads.

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4.4 Conclusion

The Hampton Roads region has a relatively low air pollution potential. This is due to the local topographic features and the geographic arrangement of the population centers, sparsely populated land areas, and nonpopulated water regions, in conjunction with the local wind regime and the nonfrequent occurrence of meteorological events conducive to pollution.

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REFERENCES

1. AIR WEATHER SERVICE, *"An Area Forecasting Study for the Southeastern United States,"* Technical Report No. 105-81. November 1951.

2. BASE WEATHER STATION, LANGLEY FIELD, VIRGINIA, *"Studies on Local Forecasting,"* Weather Division, Headquarters Army Air Forces, Washington, D. C. October 1944.

3. BIERLY, EUGENE W. AND E. WENDELL HEWSON, *"Atmospheric Diffusion Studies Near a Lake Shore,"* Journal of Applied Meteorology. Vol. 2, No. 3, pp. 390-396. June 1963.

4. CHAMBERLAIN, A. C., *"Aspects of Travel and Deposition of Aerosol and Vapour Clouds."* Atomic Energy Research Establishment HP/R 1261. 38 p. 1955.

5. CRAMER, HARRISON E., *"Engineering Estimates of Atmospheric Dispersal Capacity,"* American Industrial Hygiene Association Journal. Vol. 20, No. 3. June 1959.

6. DeMARRAIS, G. A., *"Workbook in Atmospheric Diffusion Calculations."* U. S. Atomic Energy Commission IDO-12003. 61 p. February 1959.

7. ESTOQUE, MARIANO E., *"Venting of Hot Gases through Temperature Inversions."* GRD Research Notes No. 8, AFCRC-TN-58-623. December 1958.

8. GIFFORD, JR., F. A., *"Atmospheric Dispersion Calculations Using the Generalized Gaussian Plume Method,"* Nuclear Safety. Vol. 1, No. 3, March 1960.

9. GIFFORD, JR., F. A., *"Atmospheric Dispersion,"* Nuclear Safety. Vol. 2, No. 2. December 1960.

10. GIFFORD, JR., F. A., *"Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion,"* Nuclear Safety. Vol. 2, No. 4, June 1961.

11. HILSMIER, WILLIAM F., AND FRANK A. GIFFORD, JR., *"Graphs for Estimating Atmospheric Dispersion,"* Health and Safety, ORO-545. July 1962.

12. MEADE, P. J., *"Meteorological Aspects of the Peaceful Uses of Atomic Energy,"* Technical Note No. 33 WMO-NO.97TP.41. 33 p. 1960.

13. PASQUILL, F., *"The Estimation of the Dispersion of Windborne Material,"* Meteorological Magazine. Vol. 90, pp. 33-49, 1961.

14. PASQUILL, F., *"Atmospheric Diffusion,"* London: D. Van Nostrand Company Ltd. 1962.

15. RANZ, W. E. AND H. R. JOHNSTONE, *"Some Aspects of the Physical Behavior of Aerosol Particles in the Atmosphere."* Proceedings 2nd National Air Pollution Symposium. 35 p. 1952.

16. RICHARDSON, E. G., *"Aerodynamic Capture of Particles,"* London: Pergamon Press. 1960.

17. SLADE, DAVID H., *"Climatology of Selected Harbors,"* Meteorological Research Projects Branch, U. S. Weather Bureau. April 1961

18. SLADE, DAVID H., *"A General Description of Atmospheric Motions as they Affect the Diffusion of Pollutants,"* Mimeographed Publication, Office of Meteorological Research, U.S. Weather Bureau. 1962.

19. STERN, ARTHUR C., *"Air Pollution,"* New York: Academic Press. 1962.

20. SUTTON, O. G., *"The Atom Bomb Trial as an Experiment in Convection,"* Weather, Vol. 2, pp. 105-110. 1947.

21. SUTTON, O. G., *"Note on 'Entrainment and the Maximum Height of an Atomic' Cloud by Lester Machta,"* Bulletin of the American Meteorological Society. Vol. 31, pp 217-218. 1950.

Best Available Copy

REFERENCES (CONTINUED)

22. SUTTON, O. G., "*Micrometeorology.*" New York: McGraw Hill Book Company, Inc. 1953.

23. U. S. ATOMIC ENERGY COMMISSION, "*Meteorology and Atomic Energy,*" AECU 3066. 169 p. July 1955.

24. U. S. ATOMIC ENERGY COMMISSION, "*Theoretical Possibilities and Consequences of Major Accidents in Large Nuclear Power Plants.*" Wash. 740. 105 p. March 1957.

25. U. S. ATOMIC ENERGY COMMISSION, "*Nuclear Merchant Ship Reactor Final Safeguards Report Environmental Analysis of NS 'Savannah' Operation at Camden,*" Oak Ridge National Laboratory, ORNL-2867 (Rev.). 128 p. January 1961.

26. U. S. DEPARTMENT OF DEFENSE, "*The Effects of Nuclear Weapons.*" Washington, D. C. United States Atomic Energy Commission. April 1962.

27. U. S. NAVY FLEET WEATHER FACILITY, NORFOLK, VIRGINIA, "*A Climatology of the Virginia Capes Operating Area,*" 1959.

28. U. S. NAVY FLEET WEATHER FACILITY, NORFOLK, VIRGINIA, "*Forecaster's Handbook for Norfolk, Virginia, the Tidewater Area and the Virginia Capes Operating Area.*" 1959.

29. U. S. NAVY WEATHER RESEARCH FACILITY, "*Climatology and Low-Level Air Pollution Potential from Ships in San Diego Harbor.*" NWRF 39-0462-056, 94 p. April 1962.

30. U. S. WEATHER BUREAU, "*Meteorological Estimates for Newport News, Virginia,*" Special Projects Section Office of Meteorological Research. 10 p. June 1958.

31. U. S. WEATHER BUREAU, "*Meteorological Analysis Applicable to Operation of a Nuclear Powered Vessel.*" Office of Meteorological Research. Reproduced Copy. 92 p. Rec. February 1960.

32. U. S. WEATHER BUREAU, "*Local Climatology Summary with Comparative Data.*" Norfolk, Virginia. 1962.

33. VAN DER HOVEN, ISSAC, "*A Diffusion-Deposition Model for Particulate Effluents from Ground-Tested Nuclear Engines,*" Mimeographed Report. Office of Meteorological Research, U. S. Weather Bureau 1962.

34. WILLIAMS, B. B., "*Ceilings Below 1,000 feet and Visibilities Below 1 Mile at Langley Air Force Base,*" Armed Services Technical Information Agency. AD 131682. April 1957.

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APPENDIX - EXAMPLE OF DIFFUSION CALCULATION USING THE GIFFORD MODIFICATION OF THE PASQUILL FORMULA

1. The Gifford Modification of the Pasquill formula is:

$$\chi = \frac{Q}{\pi\, \sigma_y\, \sigma_z\, \bar{u}} \exp\left[-\tfrac{1}{2}\left(\frac{y^2}{\sigma_y^2} + \frac{h^2}{\sigma_z^2}\right)\right] \quad (1)$$

where Q = total units of pollutant released

χ = ground-level total integrated dosage in units-seconds per cubic meter

$\bar{u}$ = average wind speed in meters per second

h = height of the source above the ground in meters

y = lateral (crosswind) distance from the plume axis in meters

σ_y = horizontal diffusion coefficient in meters

σ_z = vertical diffusion coefficient in meters

2. Figures 1.6 and 1.7 and table 1.1 reproduced here, and located on pages 6 and 7, are used to calculate σ_y and σ_z.

3. Example - Let us determine the axial (along the direction of the wind) total integrated dosage a person would be subjected to at a distance of 1 kilometer (10^3 meters) using the following assumptions:

(a) a summer afternoon with clear skies.

(b) a wind speed of 4 meters per second.

(c) a release of 200,000 units of pollutant.

(d) a release occurring at ground level.

The diffusion equation for axial dosage assuming ground-level release reduces to:

$$\chi = \frac{Q}{\pi\, \sigma_y\, \sigma_z\, \bar{u}} \quad (2)$$

since the y and the h in the exponential term equal zero, thereby making the exponential term equal to one $(e^0 = 1)$.

Thus:

$$\chi = \frac{200{,}000}{\pi\, \sigma_y\, \sigma_z\, (4)} \quad (3)$$

From table 1.1, a summer afternoon with clear skies results in a condition of strong insolation. A combination of strong insolation and a wind speed of 4 meters per second yields a meteorological category of type B (moderately unstable condition).

Entering figure 1.6 at the intersection of meteorological category B and an axial distance of 1 kilometer (the distance at which the dosage value is desired) we find:

$$\sigma_y = 1.6 \times 10^2 \text{ meters.}$$

Similarly, entering figure 1.7 we find:

$$\sigma_z = 1.1 \times 10^2 \text{ meters.}$$

Inserting these values for σ_y and σ_z into equation (3) we have:

$$\chi = \frac{200{,}000}{(\pi)(1.6 \times 10^2)(1.1 \times 10^2)(4)}$$

$= .092$ units-seconds per cubic meter.

Thus, at a distance of 1 kilometer, a person would recieve a dosage of .092 units-seconds per cubic meter for a ground pollutant release of 200,000 units, on a clear summer afternoon with a wind speed of 4 meters per second ($\approx$ 8 knots).

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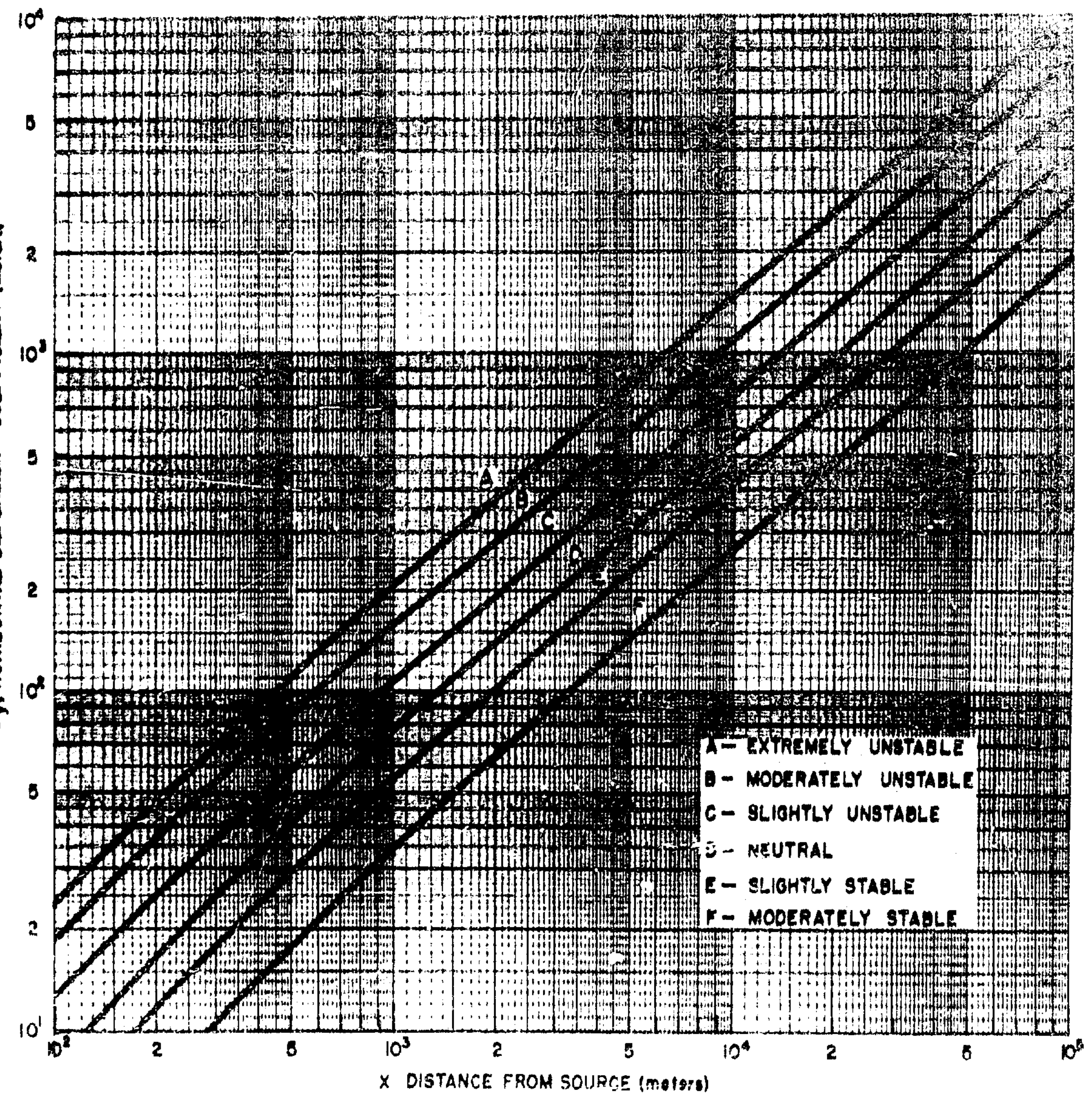

Figure 1 6. *Horizontal Dispersion Parameter σ_y (meters), as a Function of Downwind Distance, x (meters), for Various Weather Types.*

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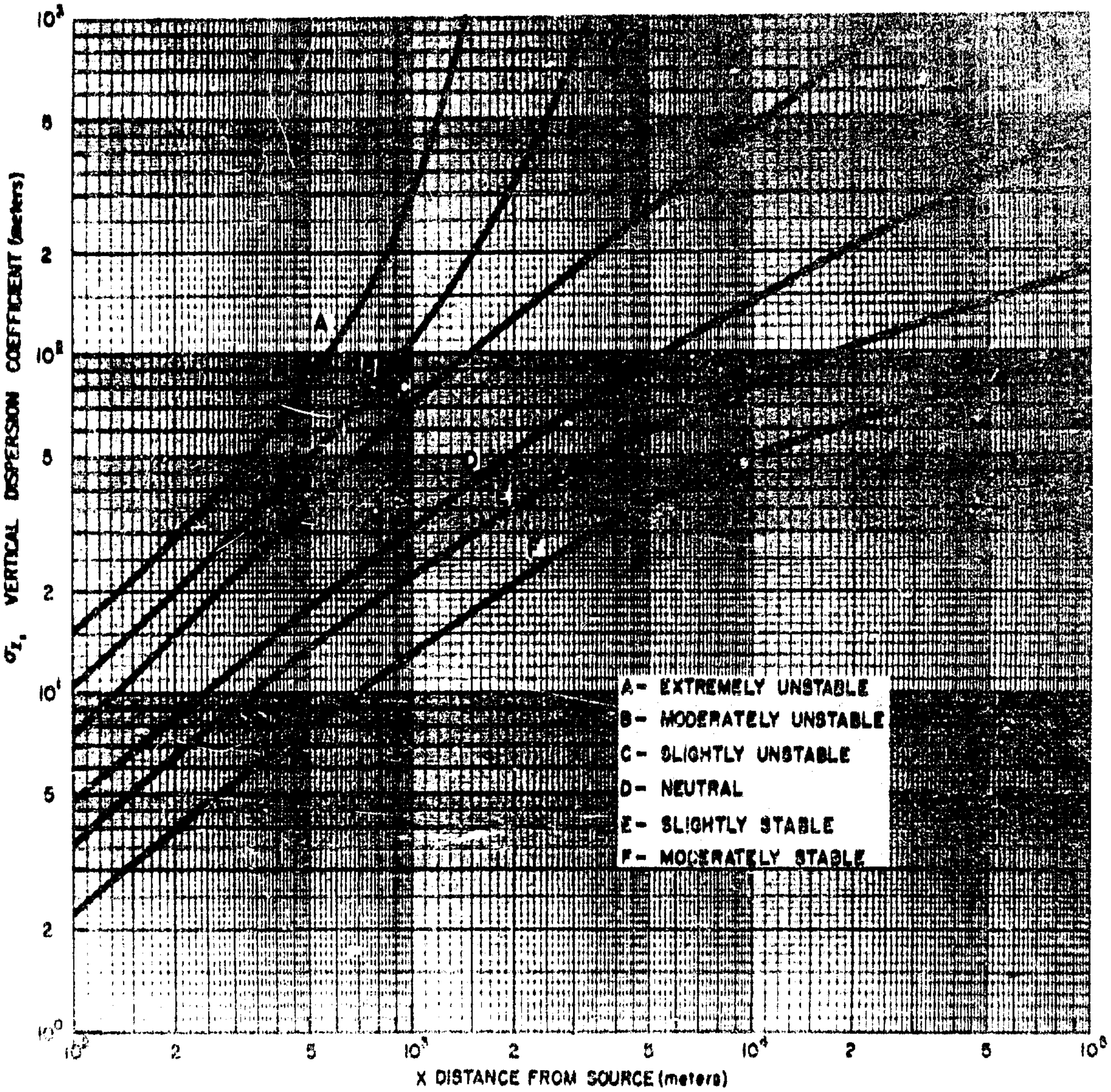

Figure A.2 Vertical Dispersion Parameter σ_z (meters), as a Function of Downwind Distance, x (meters) for Various Weather Types.

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Table 1.1 Meteorological Categories

SURFACE WIND SPEED m./sec. (knots)	DAYTIME INSOLATION Strong	Moderate	Slight	NIGHTTIME Thin overcast or $\geq 4/8$ cloudiness[1] (5 tenths)	$<3/8$ cloudiness (4 tenths)
<2 (<4)	A	A-B	B	E	F
2 (4)	A-B	B	C	E	F
4 (8)	B	B-C	C	D	E
6 (12)	C	C-D	D	D	D
>6 (>12)	C	D	D	D	D

A: Extremely unstable conditions
B: Moderately unstable conditions
C: Slightly unstable conditions
D: Neutral conditions[2]
E: Slightly stable conditions
F: Moderately stable conditions

[1] The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon which is covered by clouds. [Manual of Surface Observations (WBAN), Circular N (7th ed.), paragraph 1310, U. S. Government Printing Office, Washington, July 1960.]

[2] Applicable to heavy overcast, day or night, if ceiling is less than 7,000 feet.

Note: For A-B take the average of curves A and B; etc.

DAYTIME

Solar Altitude (α)	Insolation
$\alpha > 60°$	Strong
$35° < \alpha \leq 60°$	Moderate
$15° < \alpha \leq 35°$	Slight
$\alpha \leq 15°$	Weak (use nighttime)

Daytime Cloud Cover Effect on Insolation

1. *If clouds 5/10 or less, no change.*
2. *If clouds more than 5/10:*
   - a.) *Ceiling below 7,000, change: A to C, B to D, C to D.*
   - b.) *Ceiling 7,000 or above but below 16,000, change: A to B, B to C, C to D.*
   - c.) *Ceiling 16,000 or above and broken, no change.*
   - d.) *Ceiling 16,000 or above and overcast (heavy), change: A to B, B to C, C to D.*

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Navy Weather Research Facility (NWRF 39-0664-093)
CLIMATOLOGY AND LOW-LEVEL AIR POLLUTION POTENTIAL FROM SHIPS IN THE HAMPTON ROADS. June 1964. 72 p., including 58 figures, 2 tables, and 1 appendix.

UNCLASSIFIED

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A brief discussion of basic concepts in air pollution meteorology is followed by a general estimate of the microclimate of the Hampton Roads region.

It is concluded that the Hampton Roads area has a relatively low air pollution potential.

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This report investigates the meteorological effect upon a polluting material released into the atmosphere, within the Hampton Roads harbor area.

A brief discussion of basic concepts in air pollution meteorology is followed by a general estimate of the microclimate of the Hampton Roads region.

It is concluded that the Hampton Roads area has a relatively low air pollution potential.

1. Meteorology.
2. Air Pollution.
3. Climatology.
4. Diffusion.
5. Hampton Roads.
I. Title: Climatology and Low-level Air Pollution Potential from Ships in the Hampton Roads.
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